ROBOT-ASSISTED PEDIATRIC REHABILITATION OF UPPER LIMB FUNCTIONS

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DECLARATION

I hereby declare that the thesis is my original work and it has been written by me in its entirety. I have duly acknowledged all the sources of information which have been used in the thesis.

This thesis has also not been submitted for any degree in any university previously.

Tong Liu zhu

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12 August 2015

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SUMMARY

Cerebral palsy (CP) is considered as a neurological disorder caused by damage to the motor control centers of the developing brain. It is the leading cause of childhood disability, with an incidence of 2 to 3 per 1000 infants diagnosed each year. Impaired arm and hand functions are the most common symptoms following CP and can significantly affect the lives of the CP children.

Over the last decade, many robotic devices dedicated to upper-limb rehabilitation have been developed and tested on adults with physical disabilities. Studies of robot-assisted rehabilitation therapy for adults with physical disabilities following stroke have shown significant improvements in isolated control, strength and coordination in the impaired arm. Due to the success of this approach in adults, it is reasonable to believe that robot-assisted therapy may be well suited to the needs of children with physical disabilities associated with CP. Dedicated robotic devices can offer repetitive, intensive and frequent therapy, and automatically and progressively adapt to the patients functional abilities and precisely measure the improvements made by the patients. In addition, virtual reality games can be used to create a motivating and interactive environment and encourage patients to train as much as possible, thus increasing the intensity of treatment. Motivation for children in robot-assisted rehabilitation may be greater in comparison to adults as children are generally more interested in technology and computer games.

This thesis investigates robot-assisted rehabilitation following CP and presents the development of a novel robot, the *reachMAN2*, to train pinching, forearm pronation/supination and wrist flexion/extension; three fundamental exercises required in daily activities such as dressing, writing and eating. The robot considers the biomechanical characteristics of the human hand and can suit subjects with different hand or arm sizes. Moreover, the robot is compact, safe and easy to use. Adaptable computer games were implemented, where subjects have to actively interact with the robot while receiving interactive visual, sensorimotor or psychological feedback. This approach increases engagement, motivates training and stimulates motor recovery.

A pilot study with 7 CP children based on human-robot interaction was conducted to evaluate the possibility of using the reachMAN2 with children and whether the implemented computer games can engage the children throughout a 60-minute robotic session, which would be used in the following clinical study. With positive results from the pilot study, a clinical study was conducted to validate the effectiveness of the reachMAN2 as a rehabilitation tool. The clinical study aimed to recruit 20 CP children, 5 of which completed their 4-week robotic assisted physical therapies by the time of writing this thesis. The results suggest positive improvements in movement smoothness, speed and accuracy, muscle strength and range of motion as well as improved functional use of the affected hand or arm in activities of daily living, suggesting the possibility of using robotic devices such as the reachMAN2 to enhance motor recovery in pediatric rehabilitation. The results of this thesis provide new arguments in favor of robot-assisted pediatric rehabilitation as well as improve our knowledge on motor recovery following CP.

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Chapter 1

Introduction

1.1 Background

Children with congenital or acquired brain injury usually have impairments of their arm and hand functions. Cerebral palsy (CP), an umbrella term used to describe a group of permanent disorders in the development of movement and muscle coordination, is one of the most prevalent neurological disorders and the leading cause of physical disability, affecting approximately 2-3 in 1000 live births every year (Oskoui et al. [2013]). It is caused by the damage to the motor control centers of the developing brain, which may occur during pregnancy, childbirth, or after birth through age of 2 years (Fasoli et al. [2012]). Stroke in young children generally leads to cognitive and movement disorders which are very similar to those observed with CP (Fasoli et al. [2008]). Impaired upper limb function is one of the main problems for CP children, which can significantly affect independence and participation in activities of daily living (ADL).

CP is not only a leading disabler and killer, it is also an expensive disease. The estimated lifetime cost for persons with CP born in the United States in 2000 is around 11.5 billion dollars (Oskoui et al. [2013]). Although a lot of effort has been taken to treat and prevent complications, there is still no cure for CP. Rehabilitation is an essential part of recovery for CP children and it is typically performed in hospitals or rehabilitation centers using goal oriented activity and task-specific training to improve independence and participation in daily living (Fasoli et al. [2012]). Motor learning strategies that encompassing intensive practice, cognitive engagement, and functional relevance are believed to be important to successful therapy for pediatric motor disability (Fasoli et al. [2008]). However, it is difficult to achieve intensive practice in conventional therapy since rehabilitation sessions with the physiotherapist are cost-intensive and restricted by the limited availability of therapists.

With longer life expectancy, it is reasonable to believe that the lifetime cost for persons with CP and the number of people needed in rehabilitation services will increase in the near future. Therefore, it is necessary to investigate novel treatment solutions that can significantly improve the efficiency of rehabilitation in the paretic arm and hand with minimum cost.

1.2 Robotic devices for rehabilitation

Robot-assisted rehabilitation is one of the approaches that may reshape current clinical strategies (Hidler et al. [2005]). Studies of robotic therapy for adults with physical disabilities due to stroke have been an active field of research for the last decade and the results suggest that stroke patients can benefit from this kind of therapy. Various robotic devices have been developed and tested on adults with physical disabilities in upper limbs (Dovat et al. [2008]; Lambercy et al. [2007]; Yeong et al. [2009]). In particular, several clinical studies carried out on chronic patients suggest that robot-aided therapy of arm movements provides similar or even larger improvement of the motor function than conventional therapy (Prange et al.

[2006]; Hogan et al. [2006]; Teasell et al. [2009]).

It is reasonable to believe that robot-assisted therapy may be well suited to the needs of children with physical disabilities following CP due to the success of this approach in adults. In particular, dedicated robotic devices can provide intensive, repetitive and frequent therapy. They can precisely control the applied force, progressively adapt to the patients' abilities and record the necessary data such as position, velocity and forces or torques in real time. Virtual reality games can be used to increase motivation and engagement of the patients while training with robotic devices and encourage them to practice as much as possible. Children with physical disabilities in upper limb function may benefit from all these characteristics. Motivation for children in robot-assisted rehabilitation may be larger because they are generally both familiar with and interested in technology and virtual reality games.

In addition, children are making continual changes as they grow and mature and early life events can significantly influence both the brain architecture and behavioural development (Fox et al. [2010]). Moreover, it is commonly admitted that rehabilitation should start as early as possible. We believe that children should benefit more from robot-assisted therapy since their brains are more plastic than adults and becoming less plastic as they grow and mature.

However, in contrast to robot-assisted rehabilitation in adults, only a few studies on children with physical disabilities have been performed. The first study to inspect the feasibility and effectiveness of robotic therapy in children with upper limb disabilities was in 2008 (Fasoli et al. [2008]). Preliminary studies with children who have moderate to severe upper limb disability resulting from CP or acquired brain injury have shown that children can benefit from robot-assisted therapy (Fasoli et al. [2008]; Fluet et al. [2010]). Therefore, it is necessary to investigate more on pediatric rehabilitation using robotic devices. However, we believe that the role of robots in pediatric rehabilitation is not to replace the physiotherapists but to complement conventional therapy.

1.3 Motivation

The work in this thesis is motivated by the desire to improve the effectiveness of therapy in pediatric rehabilitation and have a better understanding of the principles underlying motor recovery in children. Currently, the therapy received by children with physical disabilities are not enough since rehabilitation sessions with the physiotherapist are cost-intensive and restricted by the limited availability of therapists. In addition, children's brains are pretty plastic at an early age and becoming less plastic while they grow and mature. Early intervention is important since early stimulation helps with developing appropriate brain architecture (Jr [2001]). In particular, evidences suggest that the development of physical activity habits in children will help establish activity patterns that continue into adulthood (Verschuren et al. [2007]). Robot-assisted rehabilitation may be a promising approach to increase the amount of therapy with reasonable costs. Furthermore, robots can offer many other advantages:

- Robotic devices can provide accurately and systematically controlled force to adapt to patients with different levels of impairments. Moreover, forces can be delivered and recorded rapidly and accurately enough to study the principles underlying neuromuscular control.
- Robotic devices are able to precisely measure and track the progress achieved by patients through the equipped sensors, which is difficult or impossible in conventional therapy through the subjective obser-

vation of therapists and patients.

- Robotic devices can provide visual feedback to the patients which may increase engagement and participation of the patients, and game-like virtual reality exercises can motivate the subjects to get more training.

During the last decade, robot-assisted rehabilitation for adults with physical disabilities has been an active research field and made significant progress, which illustrates that robots can be a useful tool in rehabilitation. However, only a few studies have been conducted on children with physical disabilities. Moreover, preliminary studies (Fasoli et al. [2008]; Fluet et al. [2010]) on children with upper limb disabilities was focused on restoring arm function, i.e. proximal part of the upper limb. Nevertheless, to perform most of the ADL such as eating, drinking and knob manipulation, arm function alone is not sufficient. In fact, hand/fingers and wrist functions, i.e. distal parts of the upper extremity, play fundamental roles to all the activities. These observations motivated new developments focusing on functions that are essential in performing ADL for children with physical disabilities and study of the principles underlying neuromuscular control.

1.4 Objectives

Despite the fact that forearm, wrist and fingers functions play fundamental roles in children's ADL, to our knowledge, no robotic device has been developed to train all these functions, especially finger functions, for children with physical disabilities. Therefore, the main objective of this study is to develop a new robotic device to train and assess all these three functions. The proposed robotic device will be tested with CP children to evaluate its effectiveness in therapy.

The second objective is to study the mechanism of neuromuscular recovery of CP children by using information or data collected with the robot during the clinical trials.

Furthermore, another main objective is to perform rehabilitation at home or in decentralized rehabilitation centers. Allowing patients to train at home or decentralized rehabilitation centers without the costs of transportation may be a promising solution to increase the amount of therapy without increasing too much costs.

1.5 Project philosophy

Hand, arm and wrist functions are fundamental in performing ADL such as eating, drinking and knob manipulation. However, based on our knowledge, currently there is no robotic device, dedicated to pediatric rehabilitation, and can offer training to the arm, wrist and hand or fingers. This motivated us to develop a new robotic device for CP children to train hand, wrist and arm functions. However, only to move the patient's hand is a very challenging task, since the human hand has 15 joints with a total of 22 degrees of freedom (DOF) and the arm from the wrist to shoulder has 7 DOF (Lum and Godfrey [2012]). We determined to train the most commonly used hand function, pinching function, to simplify the mechanism.

A technique commonly used for surgical training (Wang et al. [2004]) was used in this study to decompose the complex tasks into several subtasks to be trained individually, because it may be too difficult for CP children to perform complex tasks directly. This technique would not only simplify the mechanical design of the robotic device but also the implementation of the exercises used in the clinical study.

A good rehabilitation strategy is very critical to improve the efficiency of training with the robotic device. Interactive computer games with visual, haptic, audio as well as psychological feedbacks were implemented to increase motivation and participation of the patients. Various difficulty levels of the computer games are provided to adapt to patients' impairments levels.

A pilot study based on human-robot interaction was carried out to evaluate the developed robotic device together with the implemented computer games. The goal of this pilot study is to see whether the developed robotic system can be used by CP children and can keep them being engaged throughout a 60-minute robotic interaction, which would be used in the following clinical study.

A clinical study with 5 CP children, where the difficulty levels of the exercises were automatically adjusted, was conducted to evaluate the potential use of the developed robotic device *reachMAN2* as a rehabilitation tool.

1.6 Thesis outline

Chapter 2 introduces CP and its four main categories. Physical disabilities due to CP and conventional therapies to regain some of the motor functions are described. Robotic devices dedicated to hand or arm rehabilitation for adults and children are presented and discussed.

Chapter 3 presents the design and development of our robotic device for CP children, the reachMAN2. Detail information such as the concept for the mechanical design, the development, the implementation of the control algorithm and specifications as well as preliminary experimental results of the robotic devices are described in the chapter.

Chapter 4 describes the approach used to develop the interactive computer games for the reachMAN2. Virtual reality games for existing rehabilitation robots were first reviewed and the criteria of designing computer games dedicated to pediatric rehabilitation were developed. Based on the criteria, we implemented 3 computer games.

Chapter 5 presents the pilot study to evaluate the developed robotic device together with the implemented computer games based on human-robot interaction. The goal of this pilot study is to see whether the developed robotic system can be used by CP children and keep them being engaged throughout a 60-minute robotic interaction.

Chapter 6 describes the clinical study to validate the effectiveness of the reachMAN2 as a rehabilitation tool. The plan was to recruit 20 CP children but this thesis presents only the results of 5 CP children who had completed their four-week robotic therapies by the time of writing this thesis.

Finally, chapter 7 concludes the contributions of the work and discusses the future of robot-assisted rehabilitation in children and specifically for the robotic device developed in this work.

Chapter 2

CP and robot-assisted rehabilitation

2.1 Introduction

Over the last decade, a number of rehabilitation robotic devices have been developed and tested on adults. On contrary, only a few rehabilitation robots have been developed and tested on children. Reviewing the design and development of these devices can help us build our own robotic device.

In this chapter, we will review the four main categories of CP and conventional therapy methods used in hospitals or rehabilitation centers. Different kinds of symptoms observed in CP children can be used to guide the design of the robotic device. Various robotic devices focusing on upper limb rehabilitation for adults and children are also discussed.

2.2 CP

CP is considered as a neurological disorder caused by damage to the motor control centers of the developing brain that occurs while the child's brain is under development (Fasoli et al. [2012]). It is the leading cause of childhood disability and the most common syndrome in babies (Fedrizzi et al. [2003]). It usually occurs during the first few years of life and early signs generally appear before the age of 3 (Goldstein and Morewitz [2011]). The majority of children with CP are born with it, although the detection of CP may take months or even years. Impaired arm and hand function are the main problems and factors that significantly affect the life of the CP children (Fedrizzi et al. [2003]).

There are many possible causes for CP such as maternal infection during pregnancy, severe jaundice infection and disturbance to brain circulation prior to birth (Goldstein and Morewitz [2011]). Some children develop CP due to brain damage occurring in the first few months of life. A head injury from an accident or child abuse may cause later development of CP. In particular, Hemminki et al. [2007] found (based on around 4000 CP patients' records) that parents who had one CP child had an approximately 5 times larger risk of having a second CP child.

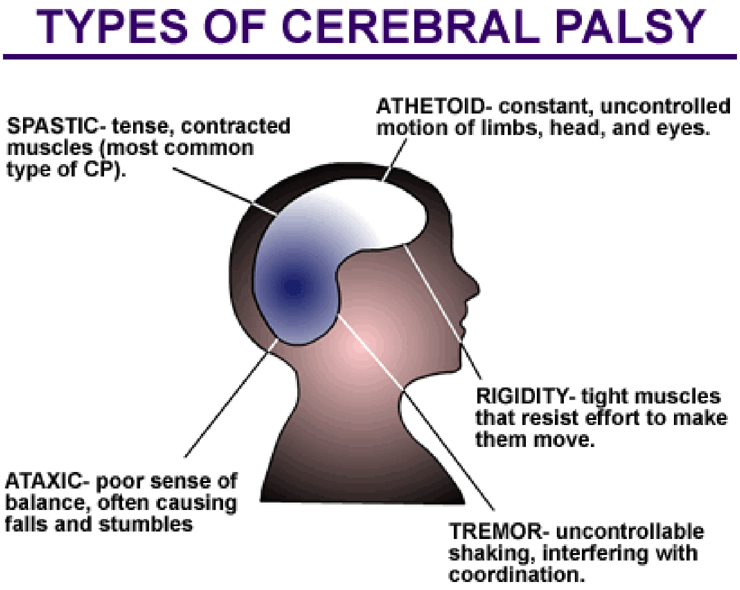

Figure 2.1: Types of CP: Spastic, Athetoid, Ataxic and Mixed. (adapted from `http://www.livingwithcerebralpalsy.com`).

CP has generally been classified in four main categories (Goldstein and

Morewitz [2011]) according to the nature of the movement disorder (Fig. 2.1):

1. Spastic CP accounts for approximately 75% of CP patients that causes muscles to stiffen, thus making movement difficult. There are 3 subsets within spastic CP: spastic diplegia which may affect the lower part of the body such as both legs, hips and/or the pelvis; spastic hemiplegia, which impacts only one side of the body; spastic quadriplegia, which is the worst form of spastic CP and may affect all four limbs and also the trunk.

2. Athetotic or dyskinesia CP is another type of CP, which impacts around one in five CP patients. It is also referred to as extra pyramidal CP, which affects the whole body and generally causes uncontrolled and slow motor functions. Generally, the child with this Athetotic CP is hypotonic at birth and has abnormal movement patterns.

3. A third type of CP is called ataxic CP, which is the least common of CP compared to spastic and athetotic CP and may affect balance and movement coordination.

4. The last type of CP, the most difficult one to treat as it is extremely heterogeneous and often unpredictable in its symptoms, is a mixture of athetoid, ataxic and spastic CP. A common combination is spastic and athetoid.

The classical distribution of CP (Fig. 2.2) is: Hemiplegia, one side of the body is primarily involved; Diplegia, the lower half of the body is primarily involved; Quadriplegia the entire body is involved.

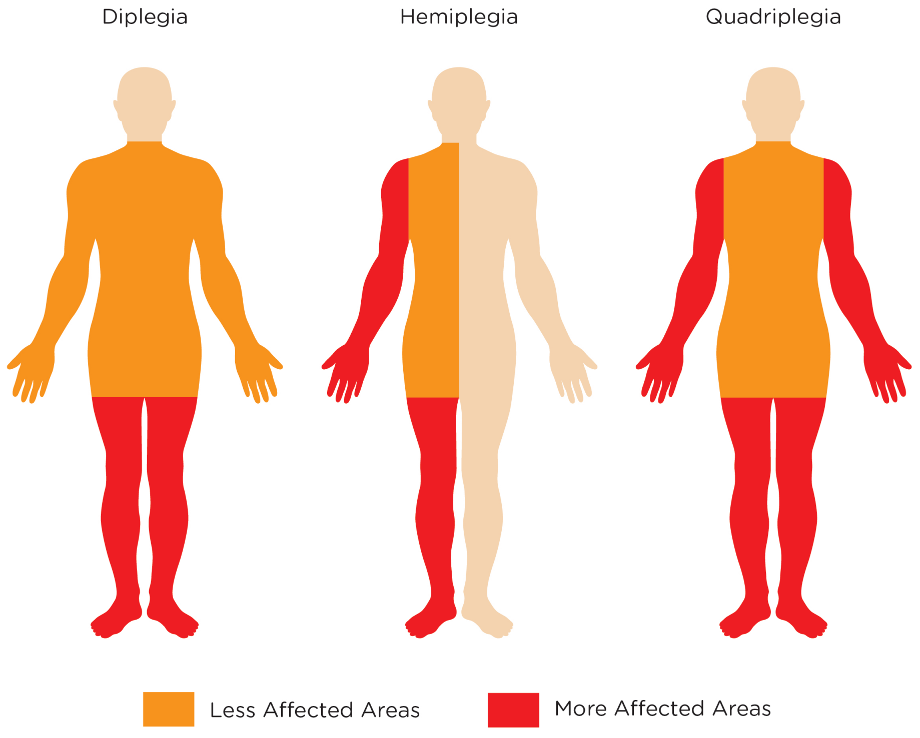

Figure 2.2: Distribution of CP: Hemiplegia, Diplegia and Quadriplegia. (adapted from `http://www.cpl.org.au/`).

2.3 Symptoms following CP

CP generally results in non-progressive syndromes of posture and movement dysfunction, which significantly affects participation and engagement in daily living. The main characteristic symptoms observed in CP children are abnormal muscle tone, muscle contracture, dyscoordination, loss of selective motor control, and muscle weakness (Jr [2001]). Loss of sensory can also affect a child's functioning. Unfortunately, there is no cure for any of these symptoms. Nevertheless, rehabilitation can help minimize the severity of these impairments, thus leading to improved functional ability.

Impaired upper limb function is the main problem in about half of the CP children (Pht and Division [2003]) and is the main factor affecting patient's participation and engagement in daily living. The previously listed symptoms, which are common in CP children with affected upper limb function, limit patient's autonomy in activities of daily living and potentially leading to permanent disabilities.

2.3.1 Abnormal muscle tone

Abnormal muscle tone is the most commonly observed symptom in CP patients (Goldstein and Morewitz [2011]). Patient may exhibit lack of muscle coordination while performing voluntary movements, exaggerate reflexes (spasticity) and stiff muscles as well as difficulty with precise movements. In medical term, muscle tone (residual muscle tension or tonus) refers to the continuous and passive partial contraction of the muscles, or the muscles resistance to passive stretch during resting state [1]. This requires robotic devices dedicated to pediatric rehabilitation should be powerful enough to overcome the muscle tone of the patients.

2.3.2 Muscle contracture

Generally, muscle contracture means that a muscle or a group of muscles has shortened significantly, thus making it difficult or impossible to achieve full range of motion of the joint or joints it crosses (Cherry [1980]). Normally, a child stretches his muscles while performing daily activities and thus achieve that muscle growth in proportion to bone growth (Russman et al. [1997]). However, children with CP cannot stretch spastic muscles adequately, which may lead to muscle contracture. Therefore, robot-assisted device designed for CP children should have enough range of motion to apply adequate stretch to muscles, thus preventing muscle contracture.

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[1] definition from `http://en.wikipedia.org/wiki/Muscle_tone`

2.3.3 Dyscoordination

Another major problem of CP children is the incoordination between the different joints due to abnormal muscles synergies. Any movement of human body is generally achieved in a synergistic pattern. In the case of the fingers, abnormal movement synergies or dyscoordination severely limit the range of motion and decrease finger independence (Lambercy [2009]), impeding activities such as typing, drinking and knob manipulation. Ricken et al. observed that the coordination of join angle pairs presented little linearity for the affected arm, indicating more segmented movements of shoulder and elbow (Ricken et al. [2005]).

2.3.4 Loss of selective motor control

The children with CP may suffer from loss of selective motor control, such as lack of control of lower extremity muscle, which significantly affects their participation in daily living (Russman et al. [1997]). Physical therapy programs can provide help and most approaches have similar principles such as development of sequence learning, training of normal movement patterns as well as prevention of deformity.

2.3.5 Muscle weakness

Muscle weakness has also long been recognized as a main clinical symptom of CP and evidence strongly suggests the fact that strength, a critical component of normal motor control, is deficient in CP and directly correlated to function performance in activities of daily living (Damiano et al. [2001]). It is defined as a drop in the maximum voluntary torque or force that can be produced under a specific set of test conditions compared to normal values and it is typically reflected by the inability of patients to generate as maximum isometric torque or force and the force or torque has been shown to be a prognostic indicator of the levels of impairments (Canning et al. [1999]).

2.3.6 Lack of sensation

A child with CP may have sensory integration dysfunction due to central nervous system damage. Sensory integration dysfunction can be defined as the inability of the brain to correctly process information brought in by the senses. Lack of sensation can result in damages which include impaired spontaneous use of the affected hand, inability to sustain grasp and effectively manipulate objects and impaired ability to reacquisition skilled movements essential to accomplish activities of daily living (Fedrizzi et al. [2003]). This reduces CP children's ability to function independently and decrease their quality of life. Therefore, the robotic devices dedicated to pediatric rehabilitation should have various types of feedback, such as haptic, visual and audio, so that the children can relearn the sensation.

These impairments are generally linked together, severely affecting the daily life of CP children. Moreover, visual and auditory problems are frequently observed in CP children. These are different from having a physical disability to see and hear things. If a child has a visual processing disability, the child may have a hard time finding the correct words for the objects they are watching. Sometimes when they are asked to get the object, they may look right at it and then respond that they cannot find it. The same goes for the auditory integration problems. The child may hear what you say, however, the brain does not process it in a way that is meaningful.

2.4 Neurorehabilitation programs

If a child is diagnosed with CP, he/she will be received by a pediatric neurologist at a hospital and start a long process of rehabilitation. This section describes the steps and methods used in the rehabilitation process for children with CP and identifies the pros and cons of conventional rehabilitation therapy used at the National University Hospital (NUH), Singapore. Fig. 2.3 shows the flowchart of the rehabilitation process for children used at the NUH, Singapore.

NUH is a tertiary hospital, which has a rehabilitation centre with occupational therapists, physiotherapists, podiatrists and speech therapists, which are all dedicated to provide holistic and integrated rehabilitation services[1].

After patients are received at NUH, they are assessed to decide which types of treatment will be used for them. For example, if the patient has difficulty in using his/her hands, specific training will be used for the hand rehabilitation. After the assessment, the patients shall receive daily sessions of physiotherapy. Functional assessments are performed every week or two weeks to keep track of the progress.

Generally, patients will receive several treatments according to their specific needs, but there are two main types of treatments, namely physiotherapy (PT) and occupational therapy (OT). Physiotherapy is a commonly used treatment intervention for children with CP (Anttila et al. [2008]), which is aimed at improving motor skills and mobility skills. It consists of stretching and exercises to strengthen muscles and help regain functional use of the limbs, and thus improving functional independence in daily life. Occupational therapy aims at training meaningful and purposely tasks which are required in daily life, for example, eating, drinking and dressing. Fig. 2.4 A and B present typical simple elastic tools that are used to train hand

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[1] information from `http://www.nuh.com.sg/`

and fingers.

After 6 to 12 months of rehabilitation therapy, the patient's improvement may plateau. Patients can continue with rehabilitation at the hospital regularly or obtain similar services in the voluntary welfare organization or community.

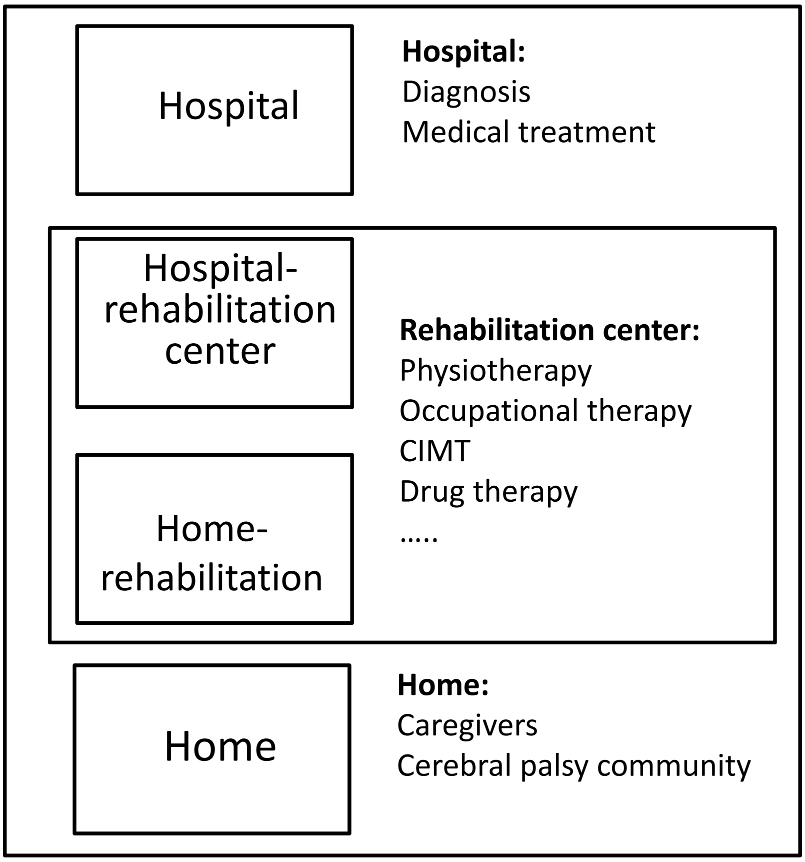

Figure 2.3: Flowchart with different steps of CP rehabilitation at NUH, Singapore.

In addition to PT and OT, there are two other main neurorehabilitation programs for upper and lower extremities used at NUH, i.e. Constraint-Induced Movement Therapy (CIMT) and Drug therapy.

CIMT: CIMT (Fig. 2.4C) is a form of rehabilitation treatment to improve hemiplegic upper extremity function by increasing the use of the impaired upper limb. This technique focuses on the combine restraint of the unaffected limb and intensive use of the impaired limb. Different types of restraints can be used in CIMT such as a sling, a splint, a half glove or a mitt (Charles and Gordon [2005]). Several studies have been carried out to prove the effectiveness of the CIMT (Wang et al. [2004]; Underwood et al. [2006]). However, this method has one important limitation, i.e. the long-time restraining of the hand during therapy, which may be too strenuous for patients. Moreover, CIMT requires that the patient should be able to perform fundamental ADL, thus it cannot be used by severely impaired patients.

Drug therapy: Botulinum toxin injection, injection of Botulinum toxin in arm or hand muscles to decrease spasticity, is one of the most commonly used drug therapies. However, Botulinum toxin injection is not a long term solution since it has to be regularly repeated to maintain improvement. Therefore, drug treatment should be a complement to traditional therapy.

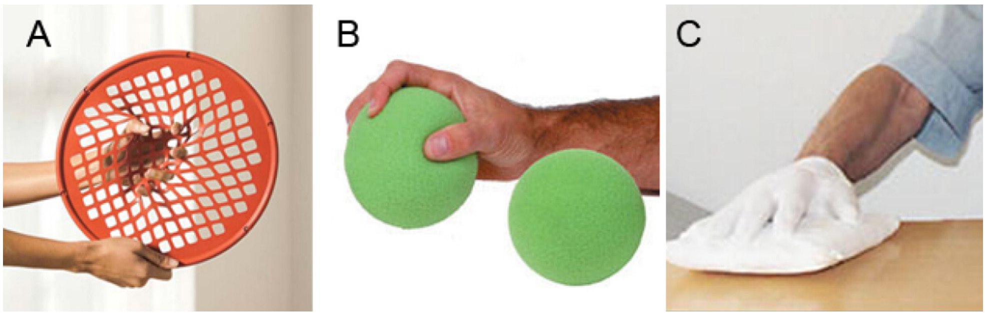

Figure 2.4: Tools used in rehabilitation centers for therapy. (adapted from Lambercy [2009]).

2.5 Rehabilitation robots for upper limb

Robot-assisted rehabilitation has been an active field of research for the last two decades and it is one of the approaches that may reshape current clinical strategies (Hidler et al. [2005]). Robotic devices can provide intensive, repetitive, adaptable and task-specific therapies for the affected limb. Using virtual-reality games may increase engagement and motivation of patients while training with robotic devices. Moreover, robotic devices provide the potential for patients to get more exercise with limited assistance. Many rehabilitation devices (Dovat et al. [2008]; Lambercy et al. [2007]; Yeong et al. [2009]) for adults have been developed and tested in the last two decades. However, there are only a few rehabilitation devices (Fasoli et al. [2008]; Keller et al. [2013]; Fluet et al. [2010]) designed for children. The results gained from the clinical studies on adults and children suggest that robot-assisted therapy may achieve better result relative to the conventional treatment. Section 2.5.1 illustrates some of the existing rehabilitation devices for adults. Section 2.5.2 shows the rehabilitation devices dedicated to children.

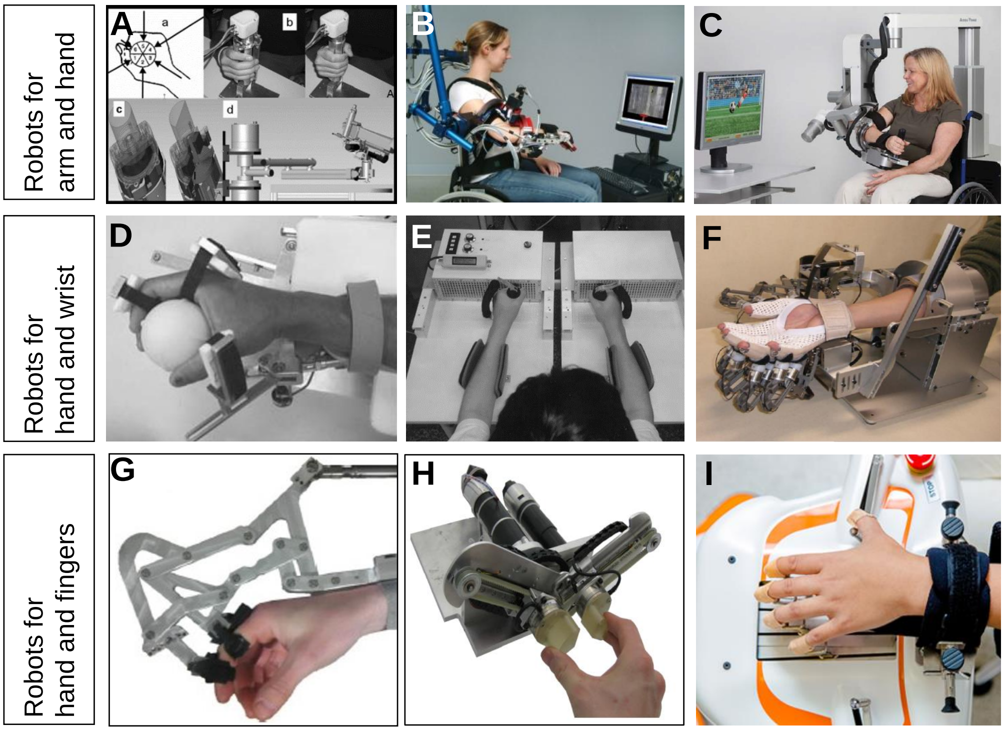

Figure 2.5: Robotic devices for hand rehabilitation. Robot dedicated to arm and hand rehabilitation: 6-DOF workstation for whole arm rehabilitation (Masia et al. [2007]) (A), the ARMin (Nef and Mihelj [2006]) (B) and the ArmeoPower (Bishop and Stein [2013] (C). Robots dedicated to wrist and hand rehabilitation: the HWARD (Takahashi et al. [2005]) (D), the BiManuTrack (Hesse et al. [2003]) (E) and the Gifu haptic Interface (Ito et al. [2011]) (F). Robots dedicated to hand and fingers rehabilitation: FINGER Robot (Taheri et al. [2012]) (G), the ReHapticKnob (Metzger et al. [2014]) (H) and the Amadeo system (Kollreider et al. [2007]) (I).

2.5.1 Rehabilitation devices for adults

2.5.1.1 Robots dedicated to arm and hand rehabilitation

Arm function plays a significant role in ADL. Several robotic devices dedicated to train arm and hand functions have been developed by several research groups.

The 6-DOF robotic device (Fig. 2.5 A) designed to train entire arm and hand functions has been developed by Masia et al. [2006] and it is an extension for their arm rehabilitation device MIT-MANUS (Masia et al. [2007]). The MIT-MANUS is a 2 DOF robotic device for shoulder-and-elbow therapy. The Hand Robot ALpha-Prototype II is a one DOF mechanism, which enables grasping rehabilitation through changing the diameter of the hand module progressively (Masia et al. [2007]). However, the robot can only train hand closing with limited range of motion and cannot train hand opening actively.

ARMin (Fig. 2.5 B) is a robotic device with 4 active and 2 passive DOF, training shoulder and elbow movements. Internal/external shoulder rotation is accomplished by a special custom-made upper arm rotary module connected to the upper arm via an orthotic shell (Nef and Mihelj [2006]). In addition, the robotic device can train elbow flexion/extension and spatial shoulder movements. However, the device cannot offer training to the fingers.

ArmeoPower (Fig. 2.5 C) is an exoskeletal robotic workstation with 6 active DOF, now commercially available, designed to train horizontal shoulder abduction, shoulder flexion/extension, shoulder internal/external rotation, elbow flexion/extension, forearm supination/pronation and wrist flexion/extension (Bishop and Stein [2013]). Moreover, the handle can measure grip pressure with the integrated sensor. However, the system is too complex and can only offer hand opening/closing training within a limited range.

2.5.1.2 Robots dedicated to hand and wrist rehabilitation

Several devices dedicated to train wrist and hand functions have also been developed. This resulted in less complex and more compact robotic devices compared to the previously described robots.

HWARD (Fig. 2.5 D) is a pneumatically actuated 3 DOF robot dedicated to train grasping and releasing movements as well as flexion/extension of the wrist. The device contacts the subject through the dorsal side of the fingers and thumb. This design leaves the palmar hand unobstructed, allowing manipulation of real objects (Takahashi et al. [2005]).

BiManuTrack (Fig. 2.5 E) is a commercially available 1 DOF device that can separately offer wrist flexion/extension and forearm pronation/supination training (Hesse et al. [2003]). The system consists two handles actuated with a master-slave system, i.e. the healthy limb drives the motion of the affected limb, allowing forearm and wrist treatments.

Gifu Haptic Interface (Fig. 2.5 F) is an exoskeleton with 18 active DOF and allows individual training for different finger joints. Specifically, it can train finger flexion/extension and adduction/abduction, wrist flexion/extension and forearm pronation/supination (Kawasaki and Ito [2007]; Ito et al. [2011]). This system is based on a master-slave system. A data glove is used to record the movement of the healthy hand and an equivalent movement is provided by the robot for the impaired hand. However, the 18 DOF makes the system very complicated. Moreover, the difficulty to adapt the exoskeleton to different hand sizes may be another drawback of the system.

2.5.1.3 Robots dedicated to hand and fingers rehabilitation

Fingers movements and independence are significant in performing ADL. Many robotic devices that can offer training of individual finger movements have been developed.

FINGER (Fig. 2.5 G) is a high-performance robotic platform designed for implementing and testing control strategies for hand rehabilitation. This robotic device is able to assist in naturalistic grasping movements of individual fingers with high control fidelity (Taheri et al. [2012]). However, this robot can only offer training to one finger and cannot be used to train arm functions.

ReHapticKnob (Fig. 2.5 H) is an end-effector-based hand rehabilitation robot and has two DOF, capable of independent control of hand opening/closing and forearm supination/pronation movements (Metzger et al. [2014]). The compact design with high stiffness enables precise assessment and dynamic interaction (Metzger et al. [2011]). However, the system cannot offer training to the wrist function.

Amadeo®[1] (Fig. 2.5 I) is a commercially available robotic device that allows the user to move each individual finger, including the thumb, independently and separately. One actuated DOF controls the linearly movements of each fingertip in a horizontal plane while a custom built sledge with 2 passive DOF enables natural orientation of the fingertip during movement (Kollreider et al. [2007]).

2.5.2 Rehabilitation devices for children

While the field of robot-assisted rehabilitation in adult has obtained significant growth in the last two decades, only a few studies have been focused

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[1] http://www.tyromotion.com/

on pediatric applications (Fasoli et al. [2012]). The specific research challenge in developing robotic devices for children is to find the correct robotic system which can satisfy the demands given by the clinical objectives, the safety constraints and the typical properties of the pediatric group (Fasoli et al. [2012]). Preliminary tests in children with robot-assisted rehabilitation devices such as the InMotion2 (Fasoli et al. [2008]) or the NJIT-RAVR (Fluet et al. [2010]) have been performed and the results suggest that robotic devices might be a very useful tool in pediatric rehabilitation. Fig. 2.6 illustrates some of the existing robot-assisted rehabilitation devices for pediatric rehabilitation.

The InMotion2, which is the commercial version of the MIT-MANUS (Masia et al. [2007]), is the first robotic device used to study the feasibility and effects of robotic therapy in children with upper limb hemiplegia (Fasoli et al. [2008]). It has 2 DOF which can train shoulder and elbow movements in a planar plane. Moreover, it provides visual and haptic feedback while the patient is performing goal-oriented planar reaching movements with the impaired upper limb. The clinical study has been conducted on twelve children with moderate to severe motor impairments and the results show significant gains in total Quality of Upper Extremity Skills Test and the Fugl-Meyer Assessment scores. However, the system can only offer therapy to the arm.

Another robotic device dedicated to children rehabilitation is NJIT-RAVR (Fluet et al. [2010]), which has 6 DOF and is the combination of the Haptic Master (Van der Linde et al. [2002]) and a ring gimbal. The Haptic Master is designed to train arm reaching in 3 dimensional plane. The ring gimbal can record the orientation angles of the forearm and use to perturbing the forearm rotation (Fluet et al. [2010]). The clinical study has been performed on 9 children and the patients demonstrated statistically significant improvements in several functional assessments of the upper limb.

However, the system cannot provide treatment for the hand or fingers.

The ChARMin, which is the children version of the ARMin (Nef and Mihelj [2006]), is a four DOF robotic device designed to train shoulder horizontal adduction/abduction, shoulder extension/flexion, shoulder internal/external rotation and elbow extension and flexion. The first prototype was fabricated and no clinical experiment has yet been performed using the robotic device (Keller and Riener [2014]). This arm exoskeleton robot can be used by children with different arm sizes through length adaptation mechanisms. However, the device is complicated and may not be suitable for home application.

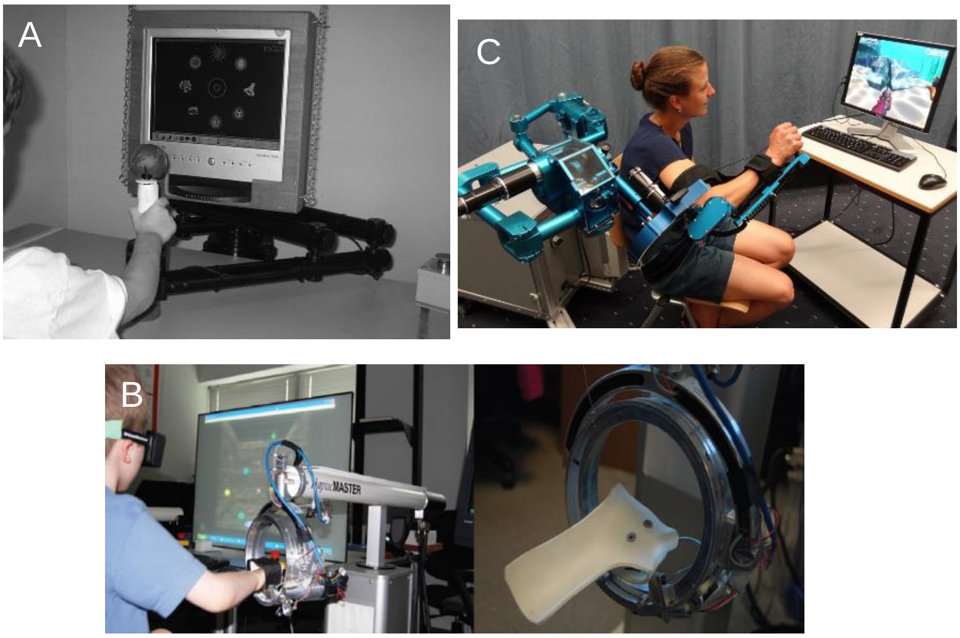

Figure 2.6: Robotic devices for children rehabilitation. InMotion2 robot (Fasoli et al. [2008]) (A); NJIT-RAVR (Fluet et al. [2010]) (B); CHARMin (Keller and Riener [2014]) (C).

2.5.3 Our robotic devices for rehabilitation

During the last decade, our research team has developed several robotic devices for adult rehabilitation following stroke. The two robots, i.e. the Haptic Knob (Lambercy et al. [2007]) and reachMAN (Yeong et al. [2009]), which are closely related to the work here, will be described in the section.

2.5.3.1 Haptic Knob

Hand function is very critical in performing many ADL such as eating, handwriting as well as knob manipulation. Therefore, our research group developed the Haptic Knob (Fig. 2.7), a two DOF robot, to train hand opening/closing and forearm supination/pronation for adults following stroke. The first DOF is a linear opening/closing of the hand, while the second one is the forearm supination/pronation. The mechanical structure of the Haptic Knob is composed of two moving parallelograms which is quite similar to an umbrella, where the user can place the fingers (Lambercy et al. [2007]). Virtual reality games were implemented to increase the motivation and engagement of the subject while training with the robotic device. Clinical study has been performed using this robotic device and the results showed significant improvements in the upper limb function, also the wrist and hand functions, especially in subjects who have less severely affected arm function (Lambercy et al. [2011]).

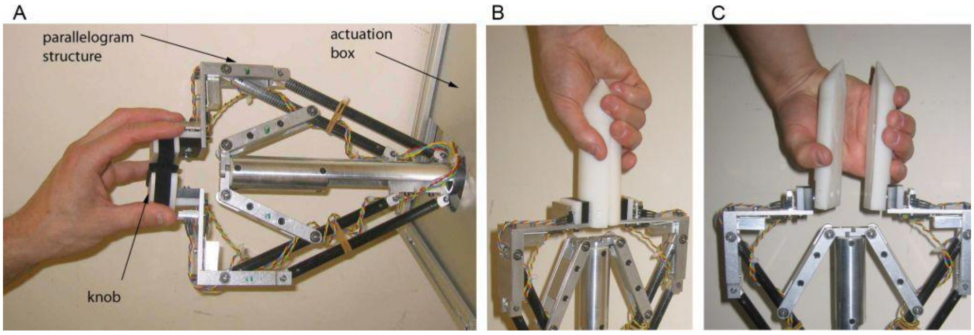

Figure 2.7: 2 DOF Haptic Knob for hand rehabilitation. A: Parallelogram structure equipped with four force sensors located close to the output, allowing measurement of grip and insertion force. Dimensions of the interface are $60 \times 30 \times 25 cm^3$. Different fixtures can be used to interact with the subject, depending on the level of impairment. A cone mechanism mounted on the Haptic Knob can be used to train a complete opening movement, from a strongly contracted and closed hand (B) to a widely opened position (C) (adapted from Lambercy et al. [2007]).

2.5.3.2 reachMAN

Robotic devices able to train both reaching and manipulation are generally large and complicated thus making them not suitable to use at home or in rehabilitation centers (Yeong et al. [2009]). Therefore, our research group developed the reachMAN (Fig. 2.8), a 3 DOF robotic device, to train arm reaching, forearm supination/pronation as well as hand opening/closing, but is still fairly compact (Yeong et al. [2010]). The design considers only the DOF which are essential to perform tasks such as drinking, eating and knob manipulation, thus making the system compact with only 3 DOF and capable of reaching and manipulation training. Preliminary results on 6 subacute patients showed significant improvement in their upper limb motor functions, range of motion, movement smoothness and decrease in movement duration (Yeong et al. [2010]).

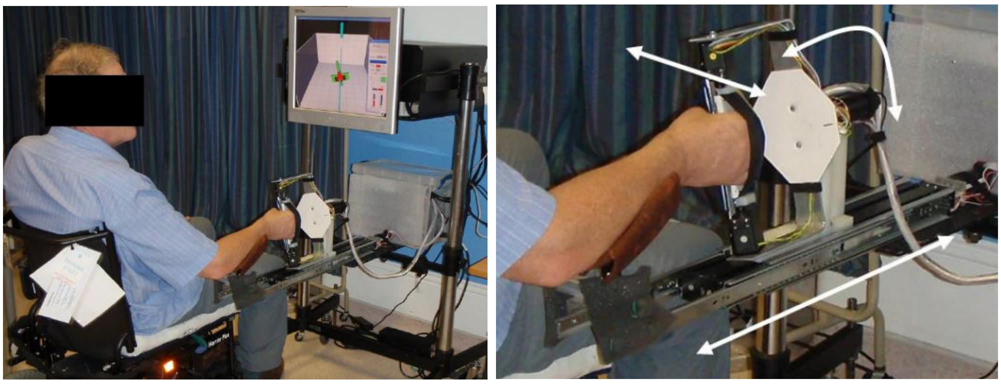

Figure 2.8: 3 DOF reachMAN for reaching and manipulation (adapted from Yeong et al. [2010]).

2.5.4 Synthesis

Table 2.1 and Table 2.2 summarizes some of the properties of the principal existing upper limb rehabilitation robotic devices for adults and children presented in this chapter, the movements trained by each robotic device and the total number of DOF of each robot as well as whether clinical study has been carried using the robotic device.

The main conclusions of this review are that many rehabilitation robots for adult have been developed to train both the arm and hand functions, which are significant and fundamental for human being to perform ADL. In contrast, only a few robotic devices have been developed for children rehabilitation. In particular, there is no robotic device designed for children that can offer all the training for arm, wrist and hand, which are essential in performing ADL, such as opening a door, eating and drinking. Exoskeleton systems are difficult to install and adapt to children with different bio-mechanical properties and impairments. End-effector based devices, i.e. which subjects hold during treatments in contrast to exoskeletons, may offer a more flexible solution with fewer mechanical constraints and can be easily adapt to various hand and arm sizes. Moreover, current robotic devices usually offer passive therapy, especially in hand opening. Passive treatments may increase the range of motion (ROM) and prevent joint stiffness. However, active movements generated and controlled by the subject are significant to build muscle strength, improve joint coordination and stimulate motor recovery (Lambercy [2009]). Finally, the two devices Inmotion2 (Fasoli et al. [2008]) and NJIT-RAVR (Fluet et al. [2010]) which have been clinically evaluated with children suggest that robotic devices may be a promising tool for children rehabilitation.

2.6 Discussion

Children with CP usually have impairments of their arm and hand functions, which can significantly affect independence and participation in ADL. Massed practice are believed to be important to achieve successful therapy for rehabilitation (Nudo [2003]). However, it is difficult to achieve massed practice with conventional therapy since rehabilitation sessions with physiotherapist are cost-intensive and restricted by limited availability.

Studies of robotic therapy for adults with physical disabilities due to stroke showed that stroke patients can benefit from this type of therapy, suggesting robot-assisted rehabilitation is one of the approaches that can redefine current clinical studies. It is reasonable to believe that robot-assisted therapy may be well suited to the needs of children with physical disabilities following CP due to the success of this approach in adults. Generally, motivation for children in robot-assisted rehabilitation may be larger because they are generally both familiar with and interested in technology and virtual reality games. Moreover, it is well admitted that rehabilitation should start as early as possible and children are making continual changes as they grow and mature. However, in contrast to the fruitful results of robot assisted rehabilitation for adults, only a few devices have been developed and tested on children with CP.

The overview of the various programs used in hospitals or rehabilitation centers suggests the importance of robotic devices for rehabilitation. Allowing patients to train at home or decentralized rehabilitation centers without the costs of transportation and with minimum supervision of the therapist, robot-assisted rehabilitation may be a promising solution to increase the amount of therapy with reasonable costs. However, robot-assisted rehabilitation for children is relatively new and benefits of the method still have to be investigated.

Table 2.1: Specifications of principal existing upper-limb rehabilitation robotic devices for adults.

Robotic devices	*Movements trained*	*Total DOF*	*Clinical trials*
6-DOF workstation for whole arm rehabilitation (Masia et al. [2007])	finger flexion/extension wrist abduction/adduction wrist flexion/extension pronation/supination shoulder and elbow movement	6	yes
ARMin (Nef and Mihelj [2006])	wrist flexion/extension forearm pronation/supination spatial shoulder movements	6	yes
ArmeoPower (Bishop and Stein [2013]	shoulder movements in 3D plane elbow flexion/extension forearm pro-/supination wrist flexion/extension	6	yes
HWARD (Takahashi et al. [2005])	finger flexion/extension thumb flexion/extension wrist flexion/extension	3	yes
BimanuTrack (Hesse et al. [2003])	forearm pronation/supination wrist flexion/extension	2	yes
Gifu Haptic Interface (Kawasaki and Ito [2007])	finger flexion/extension finger abduction/adduction thumb flexion/extension thumb abduction/adduction wrist flexion/extension forearm pronation/supination	18	no
FINGER (Taheri et al. [2012])	finger flexion/extension	1	no
ReHapticKnob (Metzger et al. [2014])	finger flexion/extension forearm rotation	2	yes
Amadeo system (Kollreider et al. [2007])	finger flexion/extension	3	yes

Table 2.2: Specifications of principal existing upper-limb rehabilitation robotic devices for children.

Robotic devices	*Movements trained*	*Total DOF*	*Clinical trials*
InMotion2 (Fasoli et al. [2008])	arm reaching (planar plane)	2	yes
NJIT-RAVR (Fluet et al. [2010])	arm reaching (3D plane) pinch, yaw and roll	6	yes
CHARMin (Keller and Riener [2014])	horizontal add-/abduction shoulder extension/flexion shoulder rotation elbow extension/flexion	4	no

Chapter 3

Design and implementation of reachMAN2

3.1 Introduction

Based on the knowledge of impairments following CP and of principal existing robotic devices, we have developed a novel robotic device, reachMAN2, an improved version of *reachMAN* (Yeong et al. [2009]), dedicated to pediatric rehabilitation. The robotic device aims at training fingers, wrist and forearm functions, which are used very often in activities of daily living.

This chapter presents the mechanical design and the development of the robotic device reachMAN2, a 2 DOF robot to train pinching, forearm supination/pronation and wrist flexion/extension exercises. Some detailed information such as the system requirements, design features, mechanical design and control of the device as well as preliminary experimental results with the device are presented.

3.2 System requirements

3.2.1 Compactness and portability

One of the main objectives of the project is to develop a new robotic device for CP children to use in decentralized centers or at home. Therefore, the proposed system should be as compact as possible and easy to move around. Ideally, the system should be fixed onto a platform, which should not be bigger than a normal computer table to enable portability and can also hold the device in a stationary position while offering treatments.

3.2.2 Adaptable

The subject's hand size varies from one to another. Thus, the robotic device should be versatile to adapt to various hand sizes or arm lengths. Moreover, the robotic device should be able to offer treatment to both left and right hand users. In particular, the robotic system should provide different levels of difficulties to adapt to subjects' impairment levels.

3.2.3 Safety and comfort

Safety plays a critical role in human robot interaction. Generally, to prevent any harm to the patient, three levels of safety should be implemented: mechanical hard stops, software workspace limits and physical emergency stops. In the first place, the software protection limits the movements according to the selected parameters such as range of motion, velocity and torque. Should the first safety level fail, the mechanical hard stops prevent further undesired movement of the robot. Finally, the patient or the supervisor may activate the safety button to stop the power supply to the motors. In addition, comfort is a critical factor to motivate patients to train long enough and continue to do so.

3.2.4 Motivation

Motivation is very important in rehabilitation robotic device to engage patient, thus enhancing the patient's recovery. Various computer games with haptic feedback can be used to make the training more interesting. Different feedback methods such as visual, audio or psychological can be used to encourage the patients to continue playing. If the patient passes certain difficulty level of the computer games, more challenging games can motivate the patient to get more training.

3.3 Biomechanical constraints

When designing robotic devices for human rehabilitation, human biomechanics must be taken into account to allow natural and comfortable movements. Two experiments were conducted to study the biomechanics of human hand and arm. The first one involving 10 healthy subjects (ages from 19-32, 4 females) was performed to find out how humans interact with different objects during prehension (Fig 3.1). The second one involving 10 children (ages from 6-12, 4 girls) and was performed to find out the specific dimensions for designing the robotic device. In the first experiment, the subjects were asked to take a key with only thumb and index finger, grasp a rubber band and hold a cylindrical handle. Some of the results of the first experiment together with the experiment (Lambercy et al. [2007]) conducted by our group earlier are summarized in the following points (the results of the second experiment will be discussed in next section):

- Different kinds of hand functions are commonly used in ADL. Pinching or gripping an object with the thumb and the index finger, is

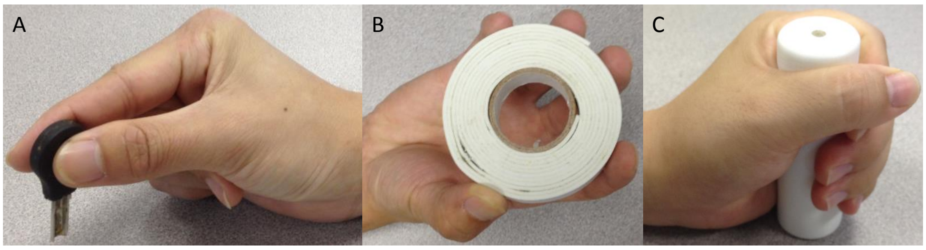

Figure 3.1: Main functions and movements of the fingers. A: Pinching, the closure of the thumb against the index finger. B: Grasp, generally involves the thumb and at least two fingers. C: Cylindrical grasp, using the side of the fingers in opposition to the thumb.

the most often used function in performing ADL such as taking a key and holding a pen. Robotic device for hand rehabilitation should offer adaptable training options which include this fundamental task.

- The analysis of the position of the fingers during prehension demonstrated that, regardless of the number of fingers involved, the thumb could always be separated from the other four fingers such that the thumb and fingers formed a jaw (Lambercy et al. [2007]), with the thumb applying forces opposite to the other fingers. Therefore, the design does not need to consider all fingers individually. Moreover, during pinching (with the thumb and index finger), the fingertips of the thumb and the index finger move in approximately the same plane. The fingertip of the index finger follows a circle around the metacarpophalangeal joint. The thumb follows a circle around the proximal phalanx joint. The design of the robotic device need to consider these biomechanics of human hand.
- The size of the hands varies from one person to another. The robotic device, especially the finger fixtures where the subject interacts directly with the device, should be able to adapt to the majority of the subjects and offer comfortable interaction.
- Typical hand functions in performing ADL generally do not need high force levels. The torques required to open or close a jar is ap-

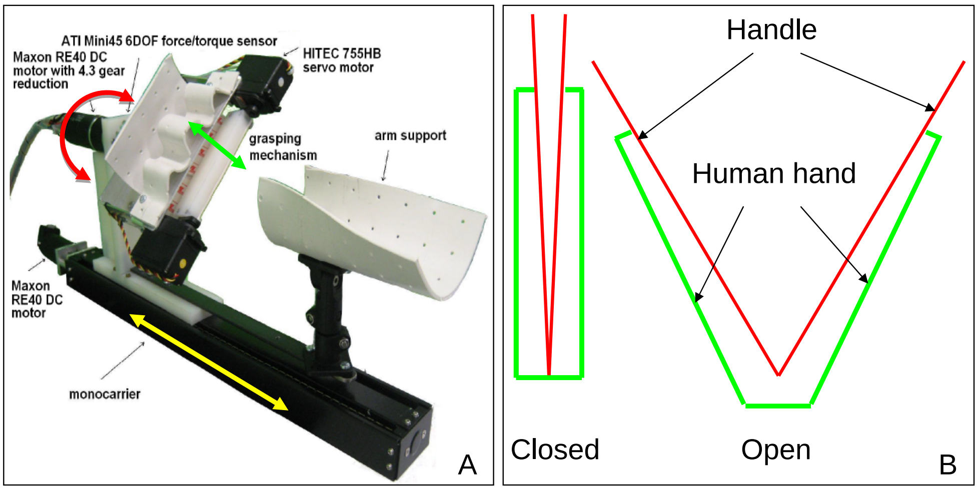

Figure 3.2: First prototype of reachMAN. A: reachMAN DOF enables training of various ADLs. B: opening-closing causes the hand to move back and forth.

proximately 0.7 Nm (Lambercy et al. [2007]), the forces needed to pinching small objects is around 10 N (Smaby et al. [2004]) and the wrist torques used to type on a keyboard is around 0.35 Nm (Rempel et al. [1994]).

- Moreover, for some people, while performing pinching movement, thumb movement is slightly slower, leading to an asymmetrical pinching movement. However, generally, in performing ADL such as taking a key, the thumb moves approximately at the same speed as the index finger since the subject usually comes to the position where the object is approximately in the middle of the thumb and index finger before they take it. This can be used to simplify the mechanical design of the robotic device.

3.4 Our robotic device

3.4.1 Modular reachMAN concept

In principle, moving the arm in position and orientation requires 6 DOF. On the other hand, often patients requiring intensive rehabilitation can initially move the hand only a few centimetres forward and cannot open the hand. Furthermore, even in healthy subjects, movements are restricted to a few DOF. The idea of reachMAN is thus to study which DOF are necessary for most important activities of daily living, and design a simple and robust robot with only such DOF (Yeong et al. [2009]).

In particular, to determine the requirements for a robot to perform rehabilitation of upper limb functions of ADL, our research group studied the kinematics and workspace requirements of three common tasks: pick-and-place, drinking and eating (Yeong et al. [2009]). Experimental results suggested that lateral deviation of the movement while performing all the 3 tasks is only 5% of the target distance, thus these activities are generally performed in a sagittal plane and the movements in these tasks can be reduced to a few DOF due to natural synergies.

Accordingly, the reachMAN design proposes using only three DOF or modules: hand open-close module, forearm pronation/supination module and arm extension/flexion or reaching module (Fig.3.2A). The combination of the linear axis, rotation and grasp (3DOF) enables training of many common functions involved in reaching and manipulation such as opening the door and taking a key, which are critical in ADL.

Similarly, for reachMAN2, we propose using a linear actuator to constrain movement in a sagittal plane, which also supports the hand movement and prevents it from diverging from the straight path line. A module for pronation/supination with an active grasping handle module, which can be

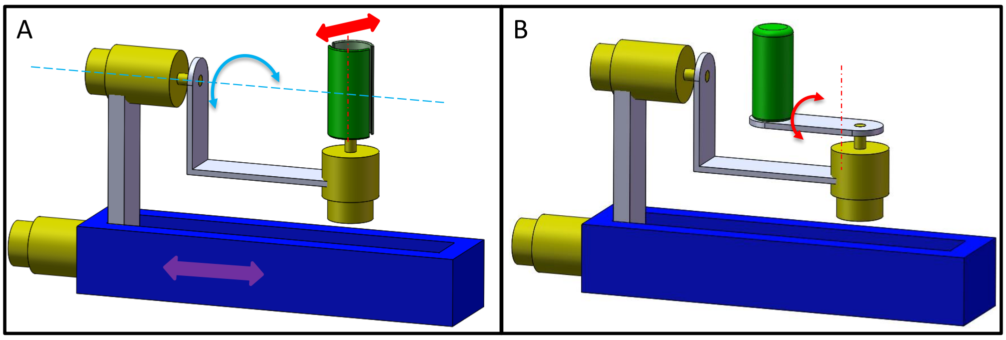

Figure 3.3: reachMAN2 robot design with different modules mounted on the linear DOF to train hand, forearm and wrist functions.

replaced by a wrist module to train wrist flexion/extension, is fixed to a liner axis.

Placing the supination/pronation module with an active grasping handle module onto the reaching module enables hand and forearm functions such as hand opening/closing and forearm supination/pronation, which are essential in knob manipulation, in the sagittal plane (fig. 3.3 A). Replacing the handle module with a wrist module, the device is able to train wrist flexion/extension, which is often used in eating and drinking (fig. 3.3 B).

During the experiments with reachMAN, we experienced that it was still relatively bulky, the access with a wheelchair (as is often needed for subacute patients) was difficult, the hand opening/closing and forearm pronation/supination were not powerful enough for some patients, and opening the hand caused the whole arm to go back and forth (Fig.3.2B). reachMAN2 addresses these drawbacks as described below.

3.4.2 Overall design description of reachMAN2

The reachMAN2 (Teo et al. [2015]) is a two actuated DOF device that allows hand opening/closing or wrist flexion/extension and forearm supination/pronation movements (Fig.3.4), with the linear reaching module locked. The first DOF serves for both pinching and wrist flexion/extension movements with one-minute of intervening mechanical adjustments. A rotation DOF enables pronation and supination around the axis of the forearm. The combination of these DOF allows training many common functional movements involved in manipulation such as grasping objects, pouring water from a cup, opening a door or using a key, which are critical in ADL. In order to make reachMAN2 compact and enable good access for patients in a wheelchair, the device is mounted upside down on a stiff motorised telescopic column with adjustable height (Fig. 3.4). This mounting strategy minimises interference with the patient's legs and enables comfortable interaction with wheelchair-bound patients.

The reachMAN2 device consists of 3 main modules, i.e. handle and wrist modules as well as forearm rotation module. Customizing the modules, especially the handle module with 3D printed finger fixtures in nylon, reachMAN2 can be used by different subjects, ranging from children to adults. It can also be custom tailored to uncommon hand impaired subjects. An innovative cam mechanism enables natural pinching movement with the index finger and thumb without the back and forth movement of the forearm (Tong et al. [2014]). Note that each module consists of few parts that can be easily redesigned and manufactured. Overall, the dimensions of the interface (without platform) are relatively small ($55 \times 18 \times 27cm^3$), with a total weight under 5 kg.

The modular design of the reachMAN2 not only allows easy customization to train different functions such as reaching, wrist flexion/extension, hand opening/closing and forearm supination/pronation individually or combinations, but also easily adapts to subjects with different hand and arm dimensions.

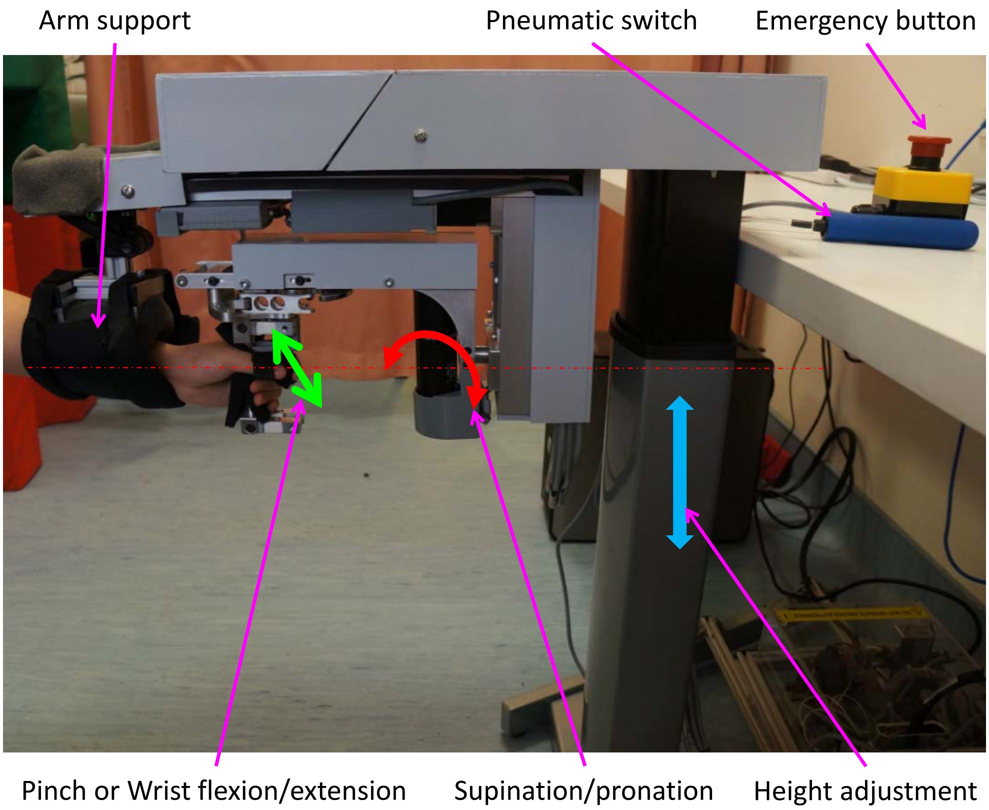

Figure 3.4: reachMAN2 for children, a compact rehabilitation robot to train pinch, forearm pronation/supination and wrist flexion/extension functions.

3.4.3 Mechanical design details

3.4.3.1 Pinch mechanism

A. Design concept

Pinching is one of the most important functions for ADL. Yet, there are only a few devices that can train the pinch function and no such device dedicated for children rehabilitation. More importantly, current robotic devices generally offer passive therapy, especially the opening part of the pinching exercise. However, it is believed that active movements initiated and controlled by the patient are necessary to build muscle strength, improve joint coordination and enhance motor recovery (Lambercy [2009]). During the experiments with reachMAN (Yeong et al. [2009]), they experienced that opening and closing of the hand caused the whole arm to go

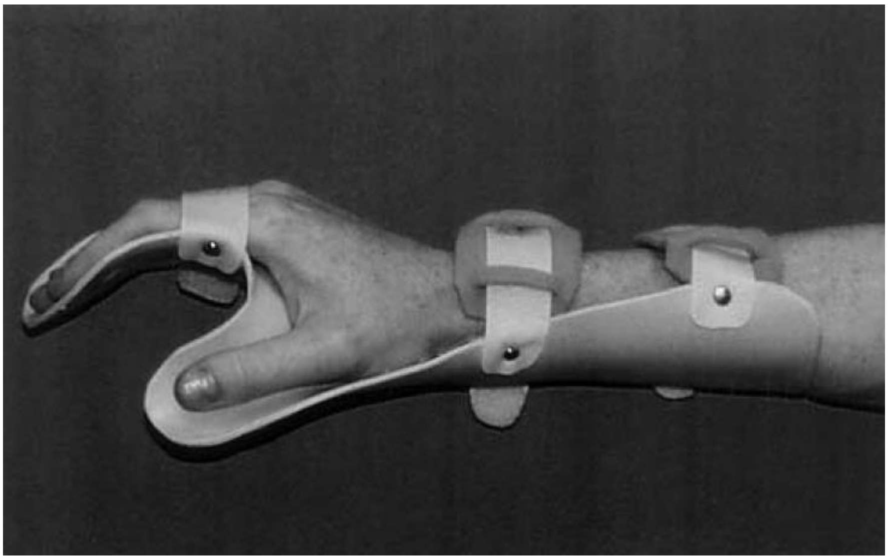

Figure 3.5: Functional position of the hand: wrist positioned at 10°-30° extension; opposition and abduction of the thumb (adapted from Lannin et al. [2003]).

back and forth due to the overlook of the biomechanics of human hand (Fig.3.2). In addition, the Haptic Knob (Lambercy [2009]) we developed for adult patients was not based on functional hand position, while training hand opening/closing exercise (Yeong et al. [2010]). Functional position of the hand denotes a position to splint the hand, wrist as well as fingers. One important characteristic of the functional position of the hand is the wrist angle (wrist positioned at 10°-30° extension) showed in Fig. 3.5 due to the dorsiflexion of the wrist. The reachMAN2 addressed these drawbacks as described later on in this section.

B. Investigated solution

Two 1 DOF mechanism (Fig. 3.6) were analysed and evaluated for the pinch mechanism. The selected design and its implementation are described as follows.

One potential solution was to use a four-bar mechanism (Fig. 3.6 A): the rotation of the middle bar opens the followers, where the hand is attached. The design is simple, easy to implement and can achieve large range of

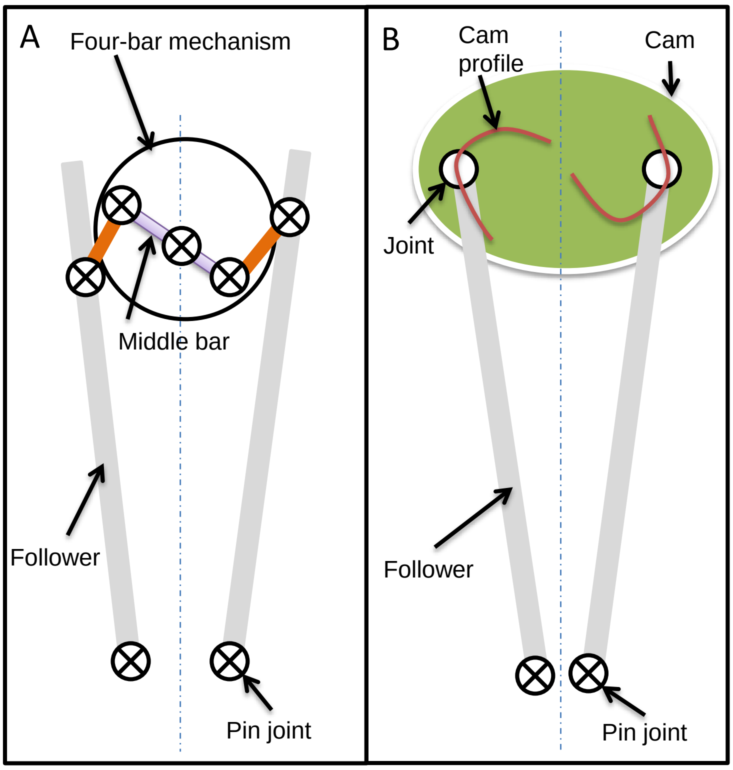

Figure 3.6: A: Four-bar mechanism solution: the rotation of the middle bar opens the followers; B: cam solution: the rotation of the cam opens the followers.

motion. However, the limitation of this system is the low force transmission efficiency of the four-bar mechanism.

Another solution, which also was the final solution, to use a cam system (Fig. 3.6 B), whose actuation generates the opening of the followers by gradually changing the lengths, from each joint to the center of the cam. While the tips of the followers sliding along the predefined red cam profiles as showed in Fig. 3.6. The design is interesting because of the excellent mechanical properties (low inertia and high rigidity) and ease of implementation. Moreover, the design is very simple and compact.

C. Cam design

1. Design Requirements

We want to design a cam-follower mechanism to open and close the human hand. The design requirements for the mechanism are:

- Simplicity: to simplify the overall mechanism, we implemented a single cam with 2 profiles driving two followers (one for the fingers and one for the thumb). We denoted the two followers R and L (Left and Right, as seen from a top view).

- Non-symmetric: hand opening does not need to be exactly symmetric for the fingers and the thumb, but the final angle between the two halves should be 90°. Furthermore, the two halves should have similar dynamic response to allow configurations for right or left handed users.

- Back-driveability: the pressure angle between the cam and the follower should prioritize the cam-to-follower transmission, although it should also (if possible) allow some back-driveability (follower-to-cam). The lower the pressure angle, the better the transmission from cam-to-follower (good transmission). High pressure angles offer good transmission from follower-to-cam back-driveability. For example, if the pressure angle is 0°, when we press on the follower the cam won't move (it has no back-driveability at all).

2. Geometry of the cam

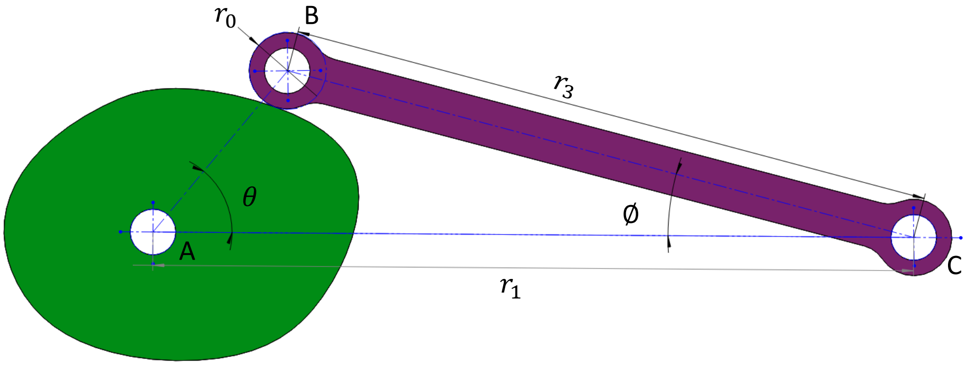

Figure 3.7: A generic cam.

A generic cam is shown in Fig. 3.7 and the parameters used to describe the cam are listed as follows:

◇ θ: cam angle.

◇ ϕ: angle of the follower.

◇ r_b: base circle radius (the length of $\overline{AB}$ when $\phi = 0°$).

◇ r_0: radius of the followers wheel.

◇ r_1: distance between pivots $\overline{AC}$.

◇ r_3: length of the follower $\overline{BC}$.

3. Cam Synthesis

We define the desired relation between input angle (θ) and output angle (ϕ). We also define the length of the follower (r_3), the radius of the followers wheel (r_0) and the distance between pivot points A and C (r_1). Our goal is to define the profile of the cam. We need to know $R_{CAM}(\theta) = \overline{AB}$.

Table 3.1: Desired relationship between input angle and output angle

θ_i	0°	20°	40°	60°	80°	100°	120°	140°	160°	180°
$\Phi_{L,i}$	0°	-5°	-10°	-15°	-20°	-25°	-30°	-35°	-40°	-45°
$\Phi_{R,i}$	0°	+5°	+10°	+15°	+20°	+25°	+30°	+35°	+40°	+45°

Based on the size of human hands, we set the values of some parameters as follows: $r_b = 10mm$; $r_0 = 3mm$; $r_1 = 60mm$; $r_{3,R} = 55mm$; $r_{3,L} = 65mm$. Table. 3.1 lists the relationship between the input angle θ_i and the output angle $\Phi_{L,i}$ and $\Phi_{R,i}$.

Therefore, we have the following relationship:

Initial position:

$$\Phi_0 = \cos^{-1}(\frac{{r_1}^2 + {r_3}^2 - r_b^2}{2r_1r_3}) = 12.55° \tag{3.1}$$

$$\Theta_0 = \cos^{-1}(\frac{{r_1}^2 - {r_3}^2 + r_b^2}{2r_1r_b}) = 60.30^\circ \tag{3.2}$$

Position of the center of the roller (x,y):

$$x_i = r_1 \cos\theta_i + r_3 \cos(\pi + \theta_i - \Phi_i - \Phi_0) \tag{3.3}$$

$$y_i = r_1 \sin\theta_i + r_3 \sin(\pi + \theta_i - \Phi_i - \Phi_0) \tag{3.4}$$

Position of the tangent point between the roller and the cam (X, Y):

$$\theta_i = \arctan(\frac{y_{i+1} - Y_i}{x_{i+1} - X_i}) \tag{3.5}$$

for $i = 0, 1, 2, 3..., n-1, n$.

Note: Equ. 3.5 holds ONLY for small $\triangle\theta$. In our case, we set $\triangle\theta = 0.1^\circ$, therefore $\theta_i = \theta_0 + i\triangle\theta$, with $i = 0...n$ and $n = 1800$.

$$\beta = \theta + \frac{\pi}{2} \tag{3.6}$$

$$\gamma_i = \arctan(\frac{\sin\beta_i - \sin\beta_{i-1}}{\cos\beta_i - \cos\beta_{i-1}}) \tag{3.7}$$

for $i = 2, 3, ..., n$.

$$\gamma_1 = \gamma_2 \tag{3.8}$$

$$X_i = x_i + r_0 \cos\gamma_i \tag{3.9}$$

$$Y_i = y_i + r_0 \sin \gamma_i \tag{3.10}$$

Table 3.2: Desired relationship between input angle and output radius

$\theta_i[°]$	0	20	40	60	80	100	120	140	160	180
$R[mm]$	18	22.26	26.60	30.96	35.31	39.62	43.86	48.07	52.19	56.22

Finally, we get the relationship $R_{CAM}(\theta) = \overline{AB}$ as shown in Table. 3.2.

However, as we found out, the rotational centers of the thumb and fingers are different during hand closing and opening. Therefore, two rotation centers, one for the thumb and one for the index finger are needed in order to achieve a more natural pinch movement. To do this, we rotate C by +7° to obtain C-R, and rotate C by -7° to obtain C-L. We do not need to recalculate $[xy]$. We can determine the new trajectory of the cam by applying a rotation matrix (Equ. 3.11) about Z axis and Fig. 3.8 shows the trajectory of the cam mechanism. Fig. 3.9 shows the final cam solution with two rotation centres and Fig. 3.10 shows the prototype of the cam.

$$M = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \tag{3.11}$$

Where $\alpha = +7°$ for right follower and $\alpha = -7°$ for left follower.

D. Handle module

The handle is a critical component of the device influencing the comfort and performance. Its design is challenging due to the complex ergonomics and biomechanics characteristics of the human hand. To study the biomechanics of the human hand, a simple experiment was carried out with 10 subjects (with ages 6 to 12, 4 females). The resulting hand dimensions are reported in Table 3.3. The index finger and thumb lengths were measured from the tip of each finger to the metacarpophalangeal joint. The hand

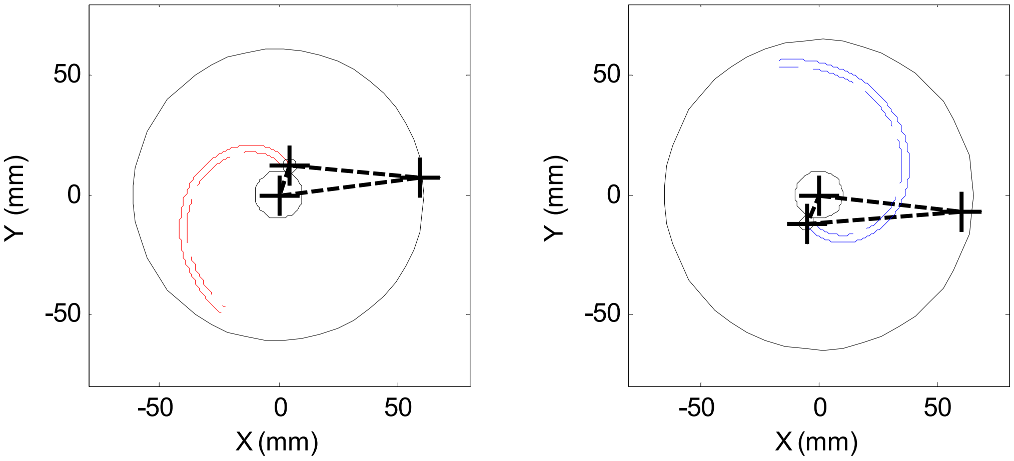

Figure 3.8: Trajectory of the centre of the cam mechanism.

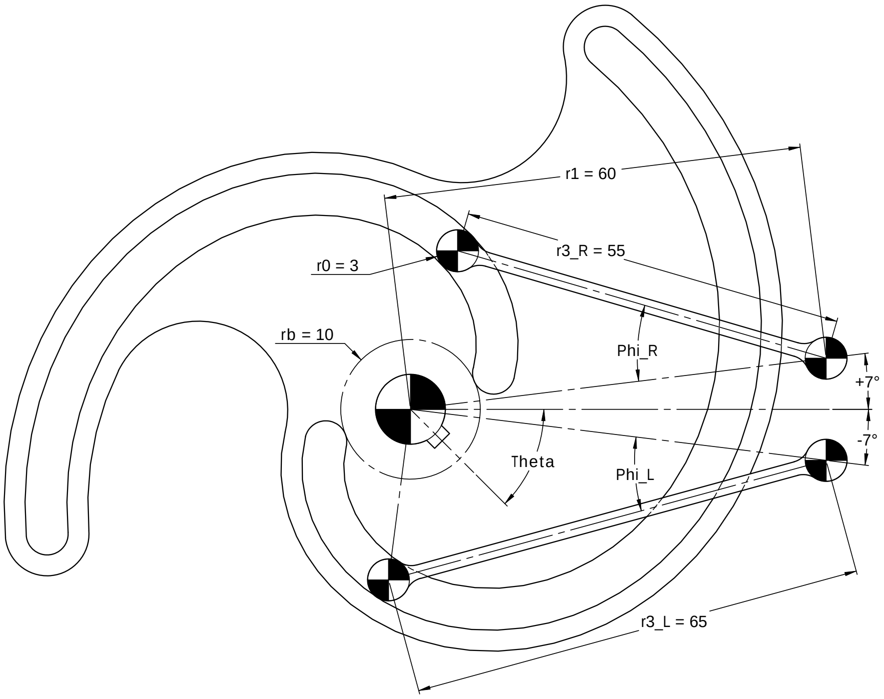

Figure 3.9: Final version of the cam.

widths were measured around the metacarpophalangeal joint. The wrist length was measured from the carpal joint to the metacarpophalangeal joint. The wrist angle δ is the wrist extension angle at the functional hand position.

To be adaptable to the majority of the subjects and offer comfortable interaction, the maximum index finger and thumb lengths, the maximum hand width and wrist length as well as the mean value of the wrist angle

Figure 3.10: Cam prototype.

Table 3.3: Biomechanics of the hand

	Mean	Max	Min
Index finger length	60mm	87mm	52mm
Thumb length	41mm	50mm	28mm
Hand width	58mm	70mm	50mm
Wrist length	61mm	72mm	50mm
Wrist angle	16°	25°	6°

listed in Table 3.3 were used to determine the dimensions of the handles for pinching, forearm supination/pronation and wrist flexion/extension.

Fig. 3.11 shows the 3D CAD model of the designed handle for pinch function implemented with the cam solution. Four force sensors (Micro Load Cell 0-20kg, CZL635)[1] are used in the handle. The two sensors at the bottom are used to measure the opening/closing forces during the pinch exercise. The other two sensors are used to calculate the supination/pronation torques during the forearm supination/pronation exercise which will be described later. The finger attachments are all 3D-printed (in nylon), which offers the possibility of rapidly prototyping with the stiffness required to adequately transmit the forces from the fingers to the force sensors. Interestingly, 3-D printing could be used to design subject specific handles, e.g. for children and adults, or for an impaired hand with specific configuration.

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[1] http://www.phidgets.com.

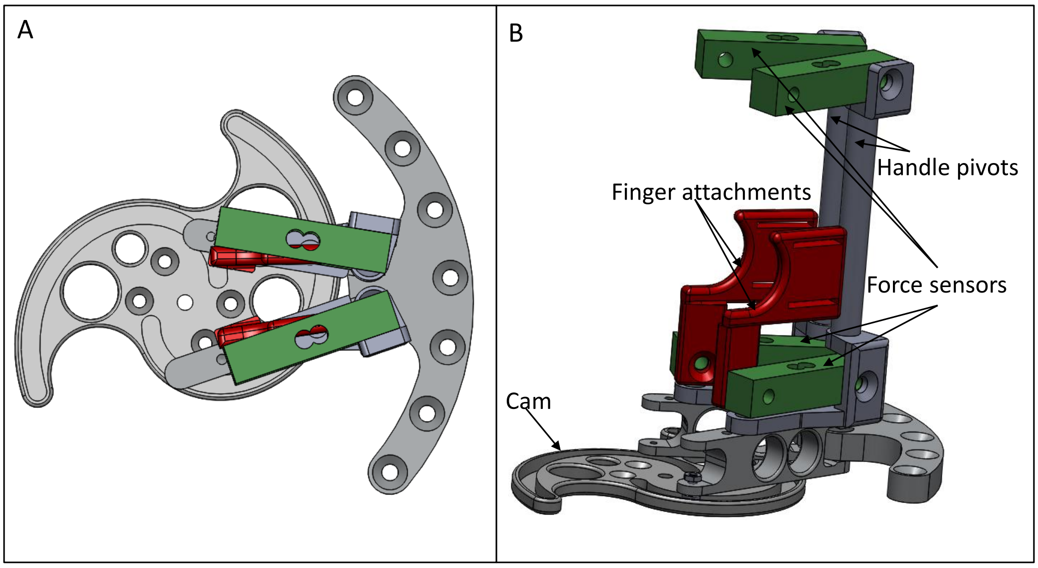

Figure 3.11: 3D model of the handle with cam solution. A: bottom view; B: side view.

The two handle pivots are the two rotation centers for the thumb and index finger. Fig. 3.12 shows the 3D CAD model of the pinch mechanism. The subject can hold it like a gun while training pinch function as shown in Fig. 3.13. Straps are used to fix the hand and the cushion placed around the plates is for increased comfort.

3.4.3.2 Wrist flexion/extension module

Wrist flexion is the movement of bending the palm down, towards the wrist and wrist extension describes the movement of raising the back of the hand toward the back of the forearm. According to the therapists, wrist flexion/extension is a significant function for CP children since their wrists are generally locked in an unnatural position, which makes it difficult for them to perform ADL. In reachMAN2, the wrist flexion/extension shares the same DOF with the pinch exercise in order to decrease the cost and simplify the design. When design the DOF, the biomechanics of the human hand need to be considered. Generally, while performing wrist flexion/extension, the wrist length (the length from the carpal joint to the

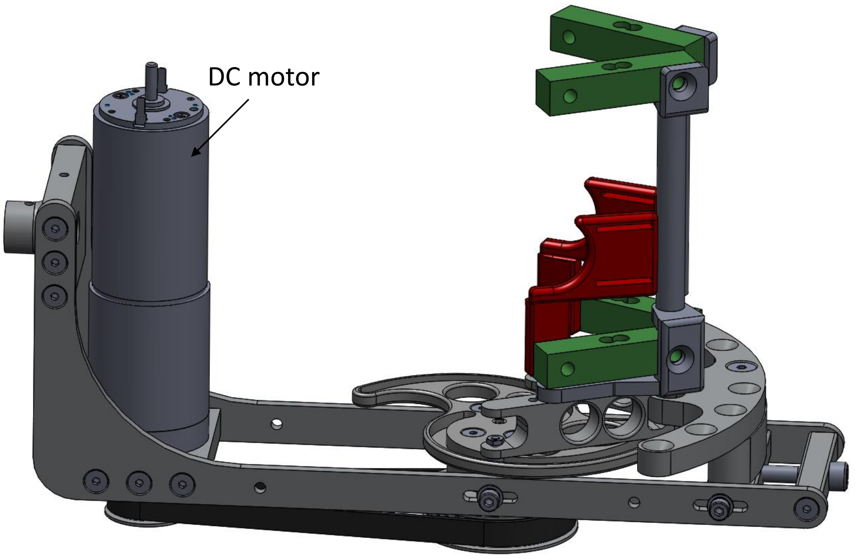

Figure 3.12: The 3D CAD model of the pinch mechanism.

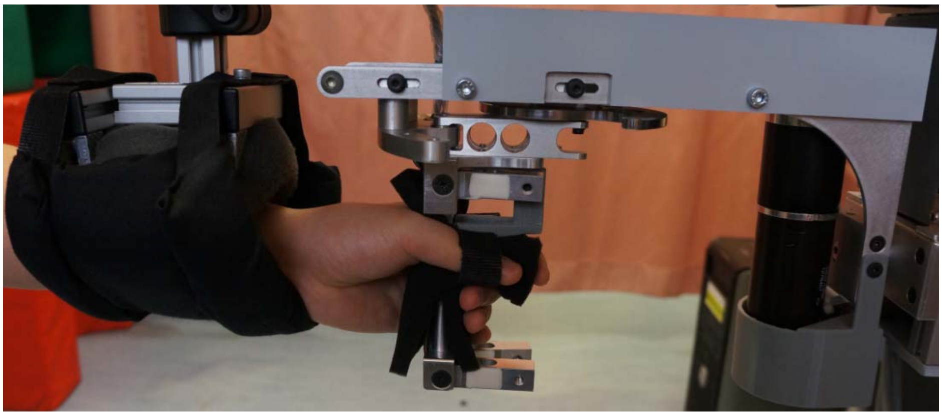

Figure 3.13: Pinch mechanism prototype, subject can hold it like a gun.

metacarpophalangeal joint) as shown in Fig. 3.14 varies from one to another. This requires that the mechanism for wrist flexion/extension to be adjustable in order to adapt to different subjects.

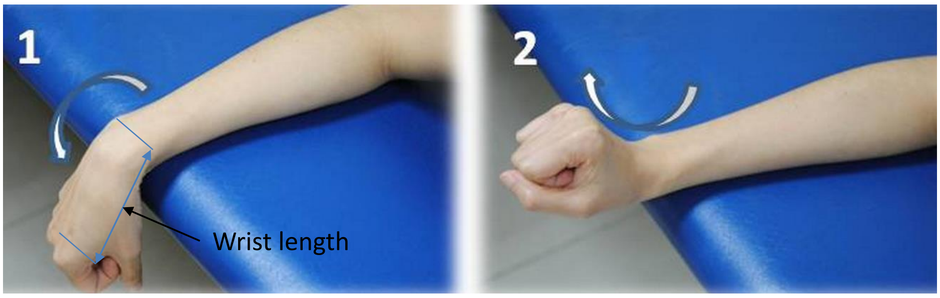

Figure 3.14: Wrist flexion/extension. Wrist length is defined as the length from the carpal joint to the metacarpophalangeal joint. (adapted from https://www.ktph.com.sg/)

Fig. 3.15 shows the CAD model of wrist flexion/extension mechanism. The arm support is used to fix the position of the arm while performing wrist flexion/extension. The adjustable plate is used to adapt to different subject with various wrist lengths. Straps can be used to fix the hand if the subject cannot hold the handle firmly. Moreover, 3D printed arm support are designed for this specific exercise since the part of forearm close to the wrist need to be fixed for the exercise. Fig. 3.16 shows subject at normal wrist positions using the robotic device.

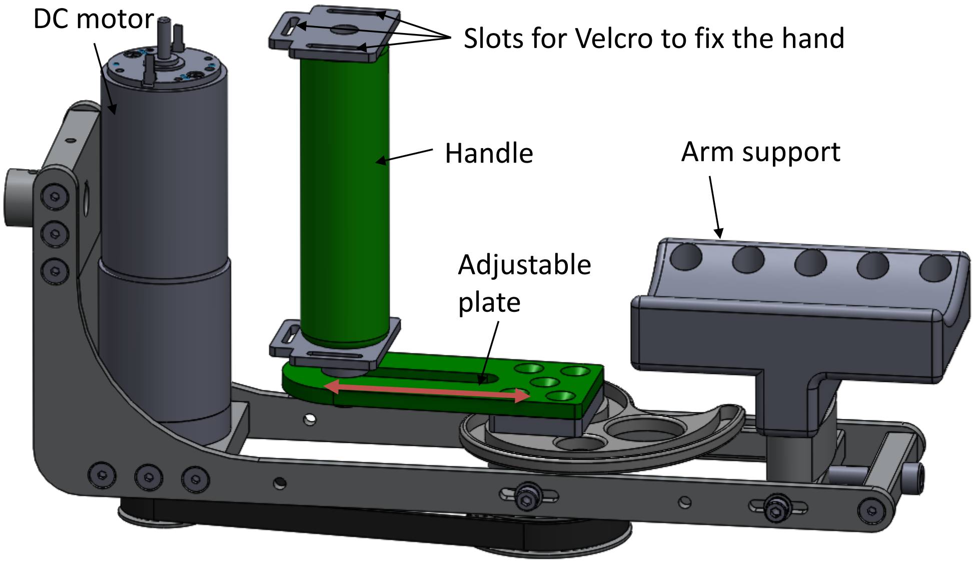

Figure 3.15: CAD model of wrist flexion/extension mechanism.

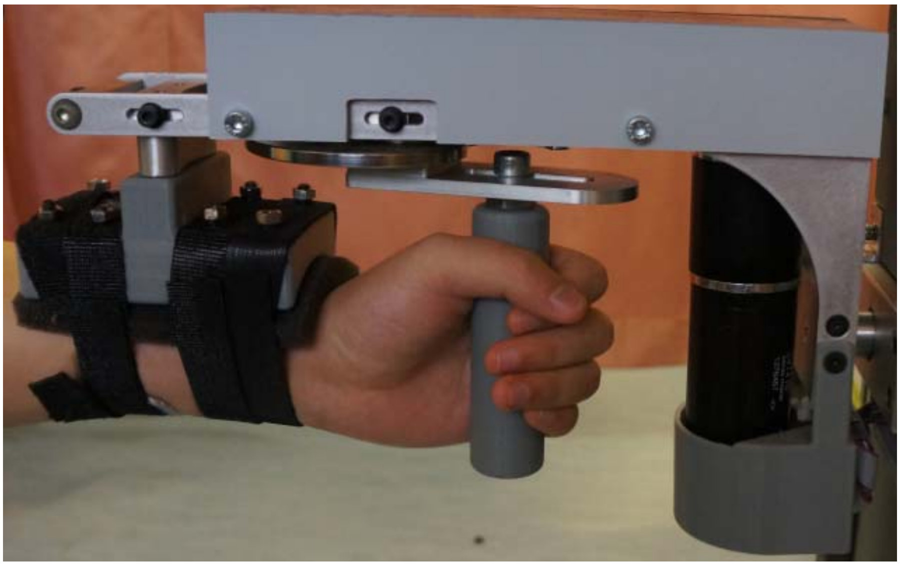

Figure 3.16: Subject at normal wrist position using the robotic device.

3.4.3.3 Forearm supination/pronation module

The second DOF of the reachMAN2 is for forearm supination/pronation. Forearm pronation is a rotational movement which rotates the forearm from palm facing up to palm facing down. Forearm supination is the opposite movement so that the palm ended facing up. In our design, we proposed to use only one actuator to train forearm supination/pronation. Fig. 3.17 shows the CAD model of the supination/pronation mechanism. A specific handle with round surface was designed for this mechanism to achieve a natural and comfortable interaction. Fig. 3.18 shows a subject at normal forearm positions using the robotic device.

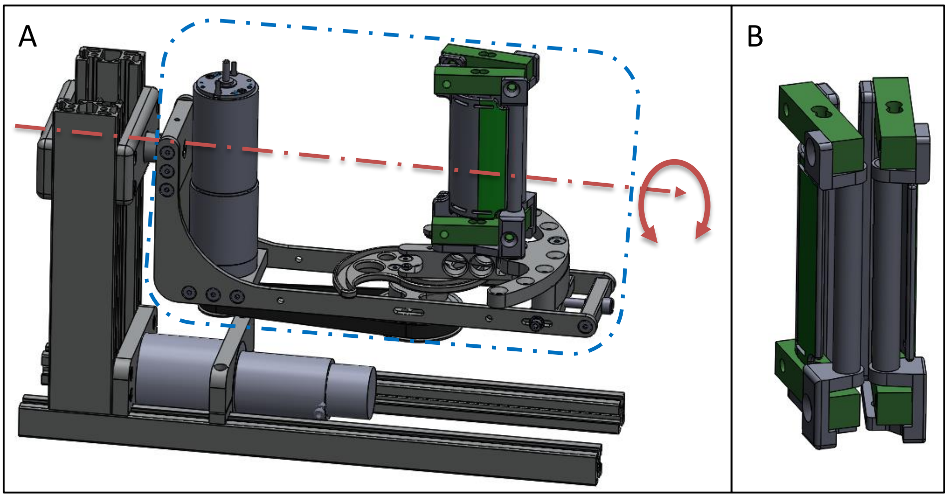

Figure 3.17: A: CAD model of forearm supination/pronation mechanism. B: Handle for the supination/pronation DOF.

3.4.4 Actuation

A brushed DC motor M1 (Maxon RE40, 150 W; encoder 500 counts/rev; gear GP42C, ratio 15:1; amplifier ADS 50/10), actuates the rotation of the cam to open and close the finger attachments or train wrist flexion/extension. A belt (B1) drive system (transmission 2:1), driven by a pulley fixed on the motor shaft, is used to transmit the power from the

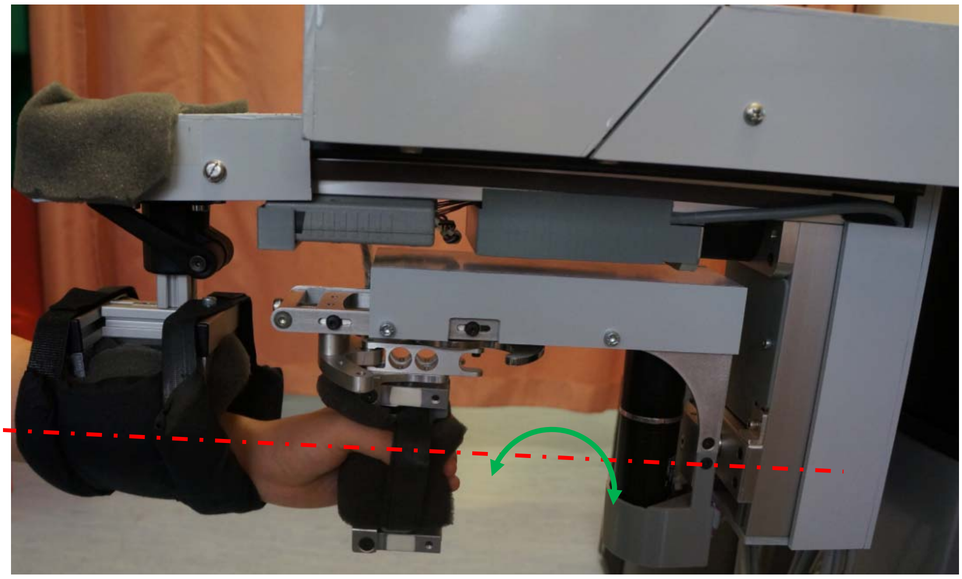

Figure 3.18: Subject at normal forearm positions using the robotic device.

motor to the cam. The slots and the big bolt as shown in Fig. 3.19 is used to adjust the tension of the timing belt B1.

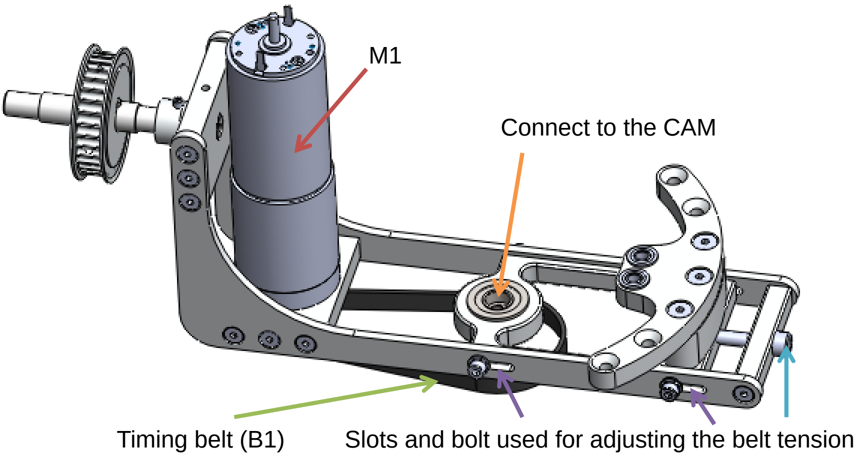

Figure 3.19: Actuation for hand opening and closing.

For supination and pronation DOF, we use a backlash free harmonic drive actuator RH-14D (gear 3002, ratio 100:1, encoder 1000 counts/rev; amplifier ADS 50/5). Due to gravity, the backlash of gear will cause a sudden rotation or a time delay when the motor change its rotation direction, which can be a danger for CP children. Another timing belt (B2) (transmission 2:1) similar to B1 is used to transmit the power from the motor to the axis of pronation and supination. The adjusting plates shown in Fig. 3.20 is used to adjust the tension of the timing belt B2.

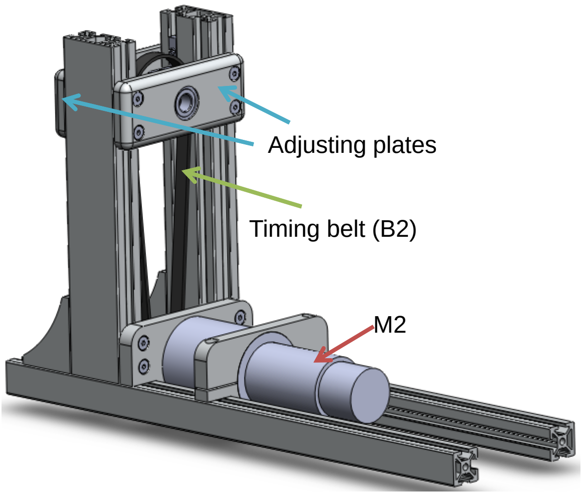

Figure 3.20: Actuation for forearm supination and pronation.

Two encoders are used to measure the output positions or angles. The relationship between the encoder output q_1 for the first DOF, q_2 for the second DOF and the output angles r_{out1-p} for pinch exercise (angle between the thumb and the index finger), r_{out1-w} for wrist flexion/extension exercise and r_{out2} for forearm supination/pronation exercise of the interface are given by:

$$r_{out1-p} = q_1 r_1 R_1 \tag{3.12}$$

$$r_{out1-w} = q_1 r_1 \tag{3.13}$$

$$r_{out2} = q_2 r_2 \tag{3.14}$$

Where $r_1 = 0.5$ is the reduction of the belt B1, $R_1 = 0.5$ is the reduction of the cam mechanism and $r_2 = 0.5$ is the reduction of the belt B2. Therefore, the inverse kinematics are given by:

$$q_1 = \frac{r_{out1}}{r_1 R_1} \tag{3.15}$$

$$q_1 = \frac{r_{out1-w}}{r_1} \tag{3.16}$$

$$q_2 = \frac{r_{out2}}{r_2} \tag{3.17}$$

3.4.5 Arm supports

While subjects are performing the exercises, it is important to have some mechanism to support their arms. Moreover, the arm support for the wrist flexion/extension exercise should be different from the one used for the forearm supination/pronation and pinch exercises since there are different requirements for the two arm supports: the one used for the forearm supination/pronation and pinch exercises is to support the rear part of the arm, thus balancing the weight of the arm, while the other one is to fix the position of the forearm as well as balance the weight of the arm. Fig. 3.18 shows the arm support designed for the robotic device while performing forearm supination/pronation and pinch functions. The position and height of the arm support can be adjusted to adapt to various subjects. The cushion placed on the arm support is for increased comfort. Fig. 3.16 shows the arm support designed for the robotic device while performing wrist flexion/extension exercise.

3.4.6 Power system design

One of the requirements for the design of the robotic device is that it should be easy to set up. This requires that the power system of the device be simple to use and also be safe and compact.

Fig. 3.21 shows the detailed information about the power system. A fuse and interrupter are used to limit the maximum current of the power system. The emergency switch and pneumatic switch are for increased safety. The holes behind the fan of the power supply are used to dissipate the heat of the system. Moreover, the interrupter can be connected to electrical network easily, just plug in and turn on the switch of the interrupter, allowing CP patients to use at home or rehabilitation centres.

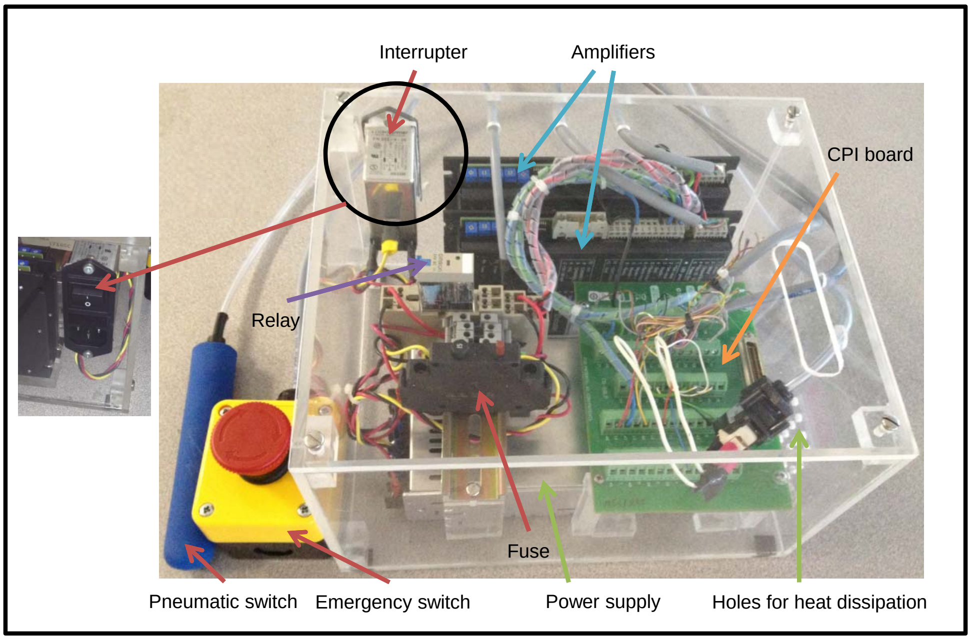

Figure 3.21: Power system.

3.4.7 Design features

The angle α shown in Fig. 3.22 can be adjusted from -30° to 30° and is used to compensate for the wrist angle (wrist positioned at an extension position) of the subject (no matter left-handed or right-handed user) in functional position of the hand.

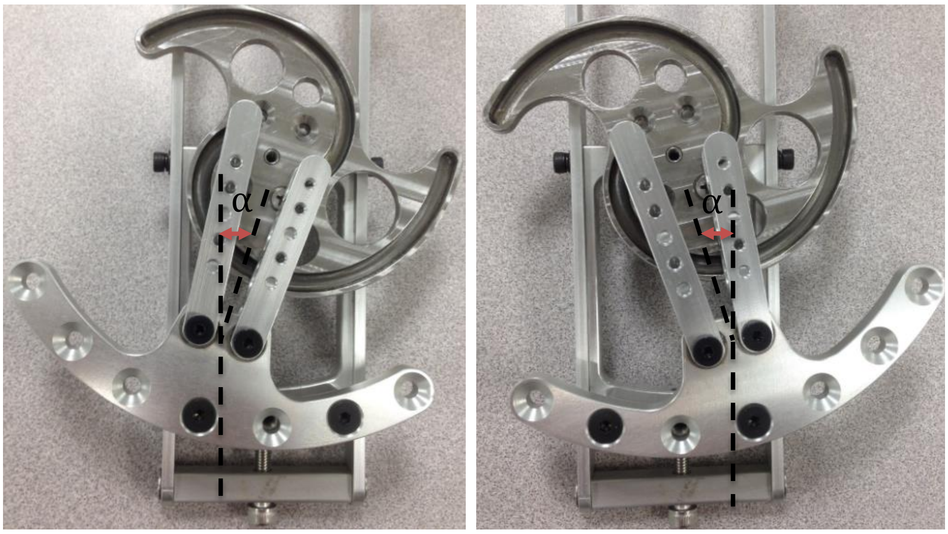

Figure 3.22: Left or right hand configuration of the designed mechanism to adapt to the wrist angles of different subjects.

Different kinds of finger attachments (Fig. 3.23) can be attached to the robotic device in order to train various hand functions such as pinching, prehension with index finger and thumb (Fig. 3.23 left) and lateral pinch, prehension with the four fingers opposite to the thumb (Fig. 3.23 right). Interestingly, 3-D printed fixtures could be used to design subject specific handles, e.g. for children and adults, or for an impaired hand with specific configuration.

Materials were chosen based on their mechanical properties, weight and comfort for the subject. The cam are made from stainless steel using high precision CNC. High precision is critical to obtain low friction and good continuous contact between the guiding grooves and the follower wheels. As for the rest of the fixtures interaction with human hand, they were 3D printed with nylon for comfortable interaction and rapid prototyping. The parts in the actuation systems (Fig. 3.19 and Fig. 3.20) were fabricated in aluminium 6061 with tolerance of 0.1mm.

The robotic device can train pinch, forearm supination/pronation as well as

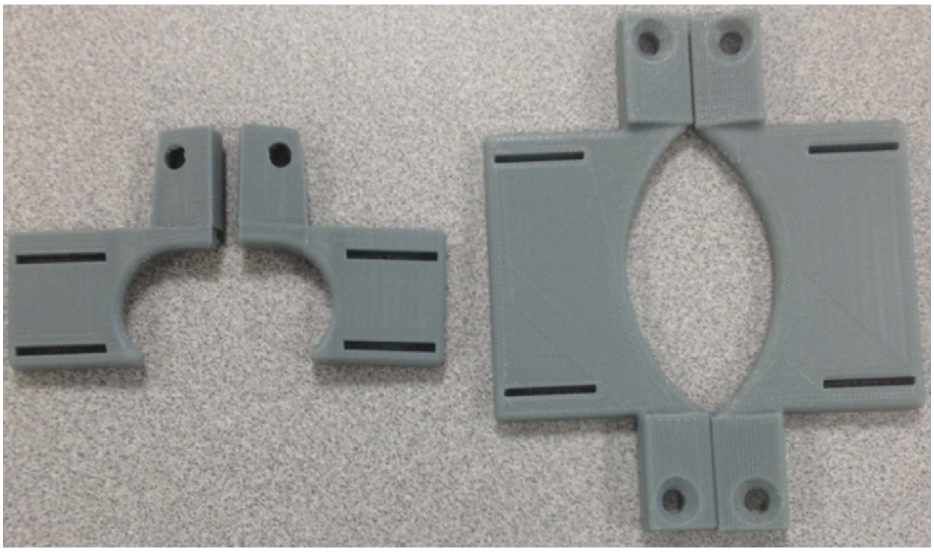

Figure 3.23: Different finger attachments that can be used on reachMAN2.

wrist flexion/extension with only 2 motors, thus simplifying the mechanism and decreasing the cost. Although some adjustments are required when switching from one type of training to another, these can be done in a very short period of time (around 2 minutes). Meanwhile subject can get some rest before the next training session.

3.5 Control

3.5.1 High level control-admittance control and impedance control

As the rehabilitation robots interact with human body, it is necessary to consider the manipulator and patient as a coupled mechanical system (Maciejasz et al. [2014]). There are two main control classes used in most of the robots for upper limb rehabilitation, i.e. impedance and admittance control. Impedance control generally accepts position or velocity as input and output force or torque. Impedance control requires that the robotic device should be backdriveable for the operator. Otherwise, the sensors can't detect any position or velocity change due to the force exerted by the operator. Impedance control strategy has been used in MIT Manus (Masia et al. [2007]) and Haptic Knob (Lambercy et al. [2007]). On the other hand, admittance control is often used in non-backdriveable systems and it accepts force or torque signal as input and react with position or velocity (Lecours et al. [2012]). Admittance control strategy has been used in reachMAN (Yeong et al. [2009]) and ReHapticKnob (Metzger et al. [2011]).

While it is generally thought that rehabilitation robots should be transparent and controlled in impedance, we believed that admittance controlled robots will be safer as they will only move if external forces are applied by the patient during the phases planed for movement. Furthermore, with admittance control small actuators can be used, and using a reduction stage, sufficient torque can be generated. For these reasons, we implemented an admittance controlled actuation for the pinch and forearm supination/pronation exercises, where the force is measured by four force sensors located on the handle, and the velocity of the end effector is computed by integrating

$$\ddot{x} = \frac{F - D\dot{x}}{m} \tag{3.18}$$

Where F is the interaction force applied by the human operator, m is the virtual mass, D is the virtual damping, $\dot{x}$ and $\ddot{x}$ are the velocity and acceleration respectively. Friction compensation, which would be discussed in the following section, was incorporated in the lower level control, the velocity controller as shown in Fig. 3.24, and resulted in a much smoother operation.

A simple impedance control method is used for the wrist flexion/extension axis since there is no force sensor used in the axis and it's backdriveable for most subjects.

$$\tau_{wrist} = w_{wrist} D \tag{3.19}$$

where the angular velocity (w_{wrist}) is measured and a reaction torque (τ_{wrist}) is fed back to the user. The robotic device can assist or resist the user with negative or positive damping (D).

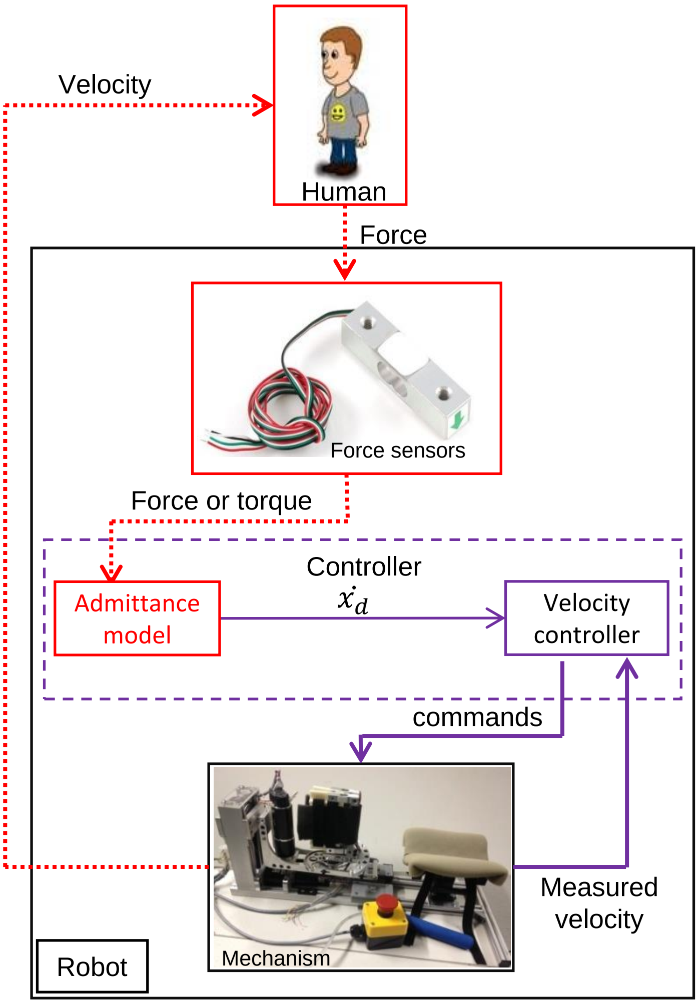

Figure 3.24: Admittance control scheme used in our robotic device.

3.5.2 Dynamic compensation

Friction is a significant source of performance degradation, especially at low velocity when the mechanical dynamics are dominated by the friction terms. Fully modelling the nonlinear friction is difficult due to the complex interaction between surface and near-surface regions of the interacting materials (Cılız and Tomizuka [2007]) and depends on many parameters such as velocity, position, temperature and lubrication (Ge et al. [2001]). We implemented a simplified friction model to compensate for the two main components of the friction: Coulomb friction and viscous friction. The Coulomb friction is a constant opposing torque for nonzero velocities, while the viscous friction is a force opposing the motion and is proportional to the velocity. The friction model was implemented using an adaptive control framework, where parameters are estimated on-line (Burdet et al. [1998]) (Fig. 3.25).

For the pronation/supination DOF of our robotic device, the frictional force is large due to the 100:1 gear reduction. Therefore, friction compensation for this DOF is critical to achieve fine motion control. Moreover, for this DOF, the output torque from the motor used to overcome the gravity varies according to the position or angle of the module. Parametric model is also available for the gravity.

Compensation for gravity, viscous and Coulomb friction in the forearm rotation axis is modelled as:

$$F_c = p_1 \sin(q) + p_2 \dot{q} + p_3 \operatorname{sgn}(\dot{q}) \tag{3.20}$$

where q and $\dot{q}$ are position and velocity, respectively. Gradient descent minimisation of the square of error

$$e(k) = q_d(k) - q(k) \tag{3.21}$$

between the desired trajectory $q_d(k)$ and actual trajectory $q(k)$ yields the adaptation law:

$$\begin{vmatrix} p_1(k+1) \\ p_2(k+1) \\ p_3(k+1) \end{vmatrix} = \begin{vmatrix} p_1(k) \\ p_2(k) \\ p_3(k) \end{vmatrix} + \lambda(k) \begin{vmatrix} \sin(q_d(k)) \\ \dot{q}(k) \\ \mathrm{sgn}(\dot{q}_d(k)) \end{vmatrix} e(k) \tag{3.22}$$

where k is the time index and λ the learning factor.

For the hand opening/closing axis, the friction is relative small. Therefore, only feedback control was used for this DOF.

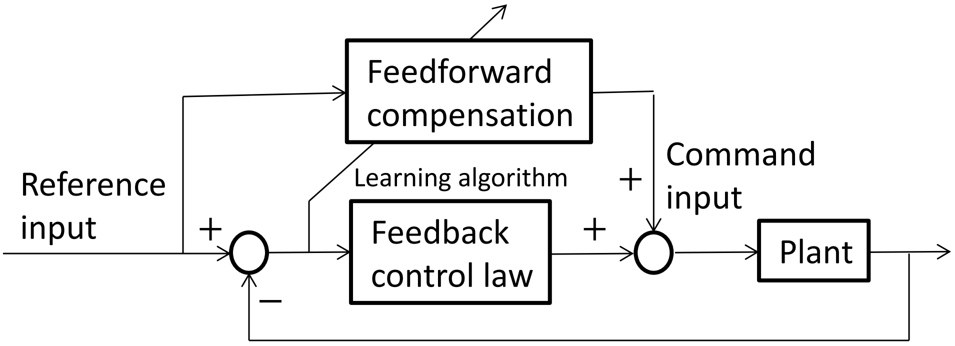

Figure 3.25: Adaptive scheme used in this work.

3.5.3 Implementation of control strategy

Our robotic device is controlled by a real-time system and implemented in Labview 2011 (National Instruments). The real-time system is composed of two elements: the target computer and the host computer. The target computer executes Labview Virtual Instrument files (VIs) on a real-time operating system and sends the signals to control the robot with control loop at 1000 Hz. The host computer executes Labview VIs on a Windows operating system and provides virtual feedback to the subject with control loop at 20 Hz. The two computers communicate with each other via an Ethernet crossover cable. Figure 3.26 presents the architecture of the control program. Data (positions, velocities and current) from the ADS amplifiers or the two motors are transferred to the RT computer through data acquisition card (PCI-6221, National Instruments). This card is also used to sample the data from force sensors at a frequency of 1000 Hz.

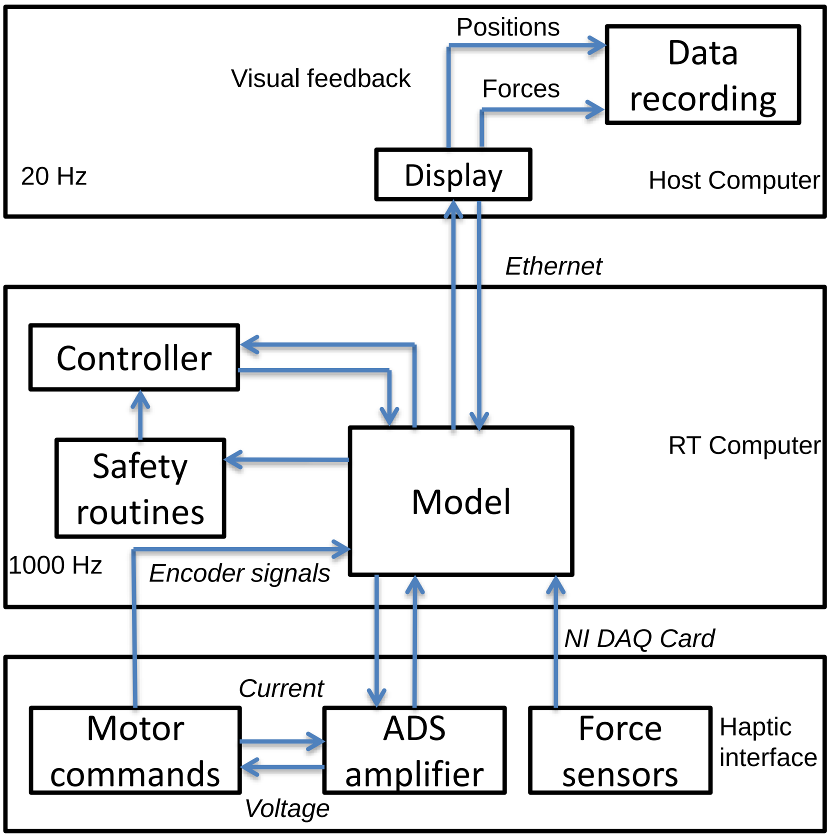

Figure 3.26: Architecture of the control program

3.6 Safety

Safety plays a very critical role in human robot interaction. To prevent any harm or damage, mechanical limitation, software protection and emergency systems should be implemented. Mechanical limitation prevents undesired movement of the robot. Software protection should limit the movements according to the selected parameters such as ROM, velocity and torque. Furthermore, redundant emergency system should allow the user to stop the movement of the robot rapidly. Safety of our robotic device is realized through:

- Low-level security surveillance routines are embedded in the motor controllers, allowing the operator to set the speed and torque/current limitations in advance. If the measured velocity or current/torque exceeds these limits, the motors will be stopped automatically.
- Mechanical ROM limitations for the two DOF of the device to prevent excessive opening $|(r_{out1})| \leq 100°$ or excessive forearm rotation $|(r_{out2})| \leq 60°$.
- Standard emergency button, which would shut down all the power, and hand-held pneumatic switch, which can only stop the motions of the motors are used for redundant safety (Fig.3.4).

Figure 3.27: reachMAN2 used by a patient (10 years old, female) at NUH, Singapore.

3.7 Performance evaluation

reachMAN2 performances and comparison with reachMAN

reachMAN2 can be used by most CP children due to its precise force or torque detection, high structural stiffness and powerful outputs. The ergonomic handle with the cam mechanism avoids the back and forth movement of the arm while performing pinch exercise as observed in reachMAN (Yeong et al. [2009]). The powered height-adjustable column can accommodate subjects with a wheelchair without disturbing the arm movement. For the interface, materials were selected based on their mechanical properties, weight and comfort for the user. The robotic device can train arm reaching, pinch and forearm supination/pronation as well as wrist flexion/extension with only 2 motors, thus simplifying the mechanism and decreasing the cost. Table 3.4 shows the properties of the device and compares them with reachMAN to underline some of the advantages such as relative smaller dimensions, lighter weight and higher output forces and torques as well as larger bandwidths. Fig. 3.27 shows the final prototype of reachMAN2 used by a patient (10 years old, female) at NUH, Singapore.

Comparison with the principal existing robotic devices

Table 3.5 shows the comparison of our robotic device reachMAN2 with the principal existing upper-limb rehabilitation robotic devices for children. The result indicates principal existing robotic devices mainly focus on the arm functions. However, hand function is very critical in performing many ADL such as eating, handwriting as well as knob manipulation (Lambercy et al. [2007]). Our robotic device is the only device that can offer active hand opening/closing training. In addition, our device is capable of providing training to arm, wrist and hand with only 3 DOF. In general, the more DOF used in a robot, the more expensive and less safe the system

Table 3.4: reachMAN2 performances and comparison with reachMAN

Robotic devices	**reachMAN2**	**reachMAN**
Hand opening/closing range	[9.02° 99.02°]	[0.05m 0.18m]
Forearm supination/pronation range	$[-60° +60°]$	[-180° 180°]
Wrist flexion/extension range	$[-90° +90°]$	N.A.
Max generated opening/closing torque	$10.2Nm$	$1.5Nm$
Max generated rotation torque	$11.8Nm$	$1.08Nm$
Max generated flexion/extension torque	$5.1Nm$	N.A.
Dimensions of the interface (without platform)	$55 * 18 * 27cm^3$	$100 * 30 * 35cm^3$
Mass of the interface (without platform)	$5kg$	$8kg$
Velocity bandwidth of forearm rotation DOF	$3.94Hz$	$1.84Hz$
Velocity bandwidth of opening/closing DOF	$3.78Hz$	$2.63Hz$
Mean opening/closing resistance at $1Hz$	$0.08Nm$	N.A.
Mean rotation resistance at $1Hz$	$0.126Nm$	N.A.
Force sensors sampling frequency	$1000Hz$	$1000Hz$
Motion control frequency	$1000Hz$	$1000Hz$
User interface update frequency	$20Hz$	$30Hz$

will be (Yeong et al. [2009]).

Table 3.5: Comparison with the principal existing upper-limb rehabilitation robotic devices for children.

Robotic devices	**Movements trained**	**Total DOF**
InMotion2 (Fasoli et al. [2008])	arm reaching (planar plane)	2
NJIT-RaVR (Fluet et al. [2010])	arm reaching (3D plane) pinch, yaw and roll (forearm)	6
CHARMin (Keller and Riener [2014])	shoulder horizontal add-/abduction shoulder extension/flexion shoulder rotation elbow extension/flexion	4
reachMAN2	arm reaching forearm supinaiton/pronation wrist flexioin/extension hand opening/closing	3

Friction of the cam mechanism

For the cam mechanism, it is significantly important that the rollers can slide within the designed grooves smoothly so that the motor we use for this DOF can drive the cam mechanism to open and close human hand. Fig. 3.28 shows the position signal of the cam (top) and the corresponding torques measured with (red) and without (green) the rollers and followers plugin the cam. It can be seen that the two torques under the two conditions are roughly the same, indicating that the rollers can smoothly slide within the designed grooves of the cam.

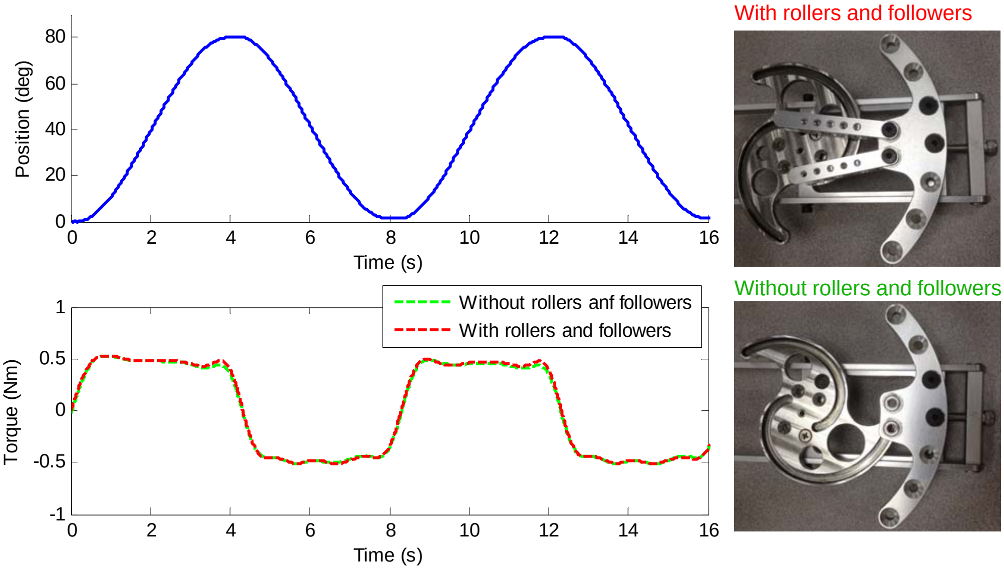

Figure 3.28: Friction of the cam mechanism. Position signal of the cam (top). Torque signals (bot) measured with (red) and without (green) the rollers and followers plugin the cam.

Various hand opening training

Fig. 3.29 displays representative trials of a healthy subject performing different hand opening movements with various finger attachments (as shown in Fig. 3.23) mounted on the interface of the reachMAN2. It can be seen that thumb plays a dominant role while performing hand opening with only thumb and index finger (bottom), which is different from hand opening with thumb and the other four fingers where the four fingers dominate thumb (top).

Dynamic performance of the impedance control

The dynamic performance of the robotic device is capable of generating force and torque as functions of position and velocity. Fig. 3.30 (left) shows the effect of destabilization caused by a position dependent torque

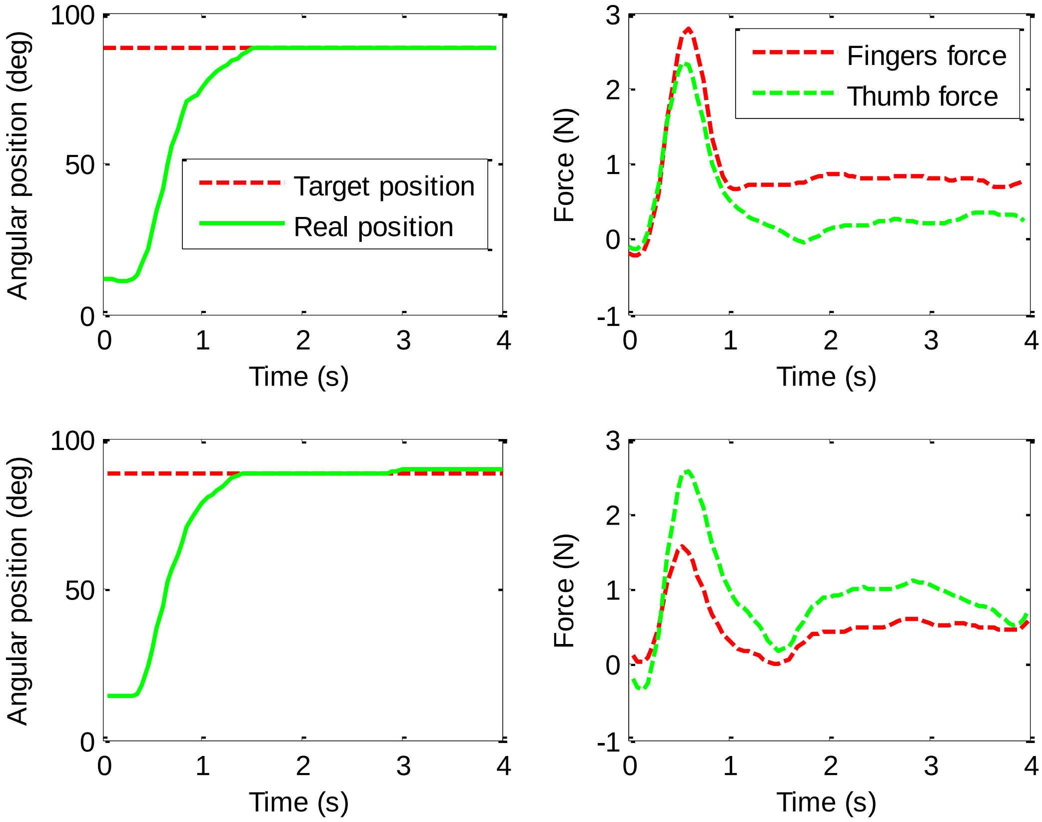

Figure 3.29: Hand opening movement with thumb and four fingers (top). Hand opening movement with thumb and index finger (bottom). Both movements were performed with the implemented control program described.

(Equ. 3.23) with negative stiffness ($K < 0$) implemented on the wrist flexion/extension DOF, which can be used to magnify movement error as shown in the figure.

$$\tau = K\theta_{in} \tag{3.23}$$

Fig. 3.30 (middle and right) presents the effect of a velocity dependent torque (Equ. 3.24). Positive damping ($D > 0$) can be used to produce a velocity-dependent assistive torque to assist weak users and negative damping ($D < 0$) can be used to provide a velocity-dependent resistive torque to build muscle strength. Similar effects are possible with the pinching and forearm supination/pronation DOFs of the reachMAN2.

$$\tau = D\dot{\theta}_{in} \tag{3.24}$$

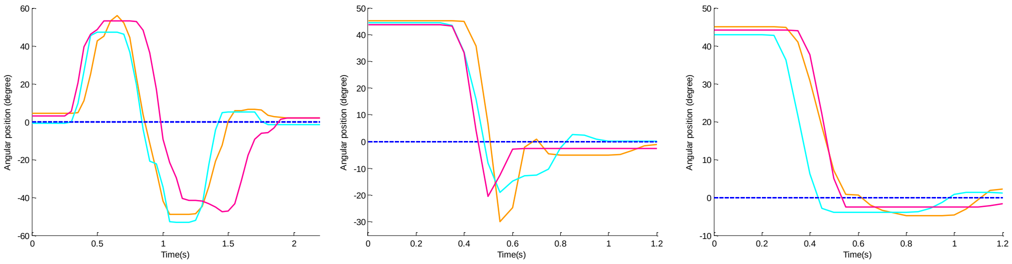

Figure 3.30: Wrist flexion/extension movements of a healthy subject with the reachMAN2. Dashed lines denote the target position. Movements with a position dependent toque (left). Movements with a velocity-dependent assistive torque (middle) and with a velocity-dependent resistive torque (right).

Dynamic performance of the admittance control

In order to test the performance of the admittance control, a healthy 27 years old male was asked to follow a 16° sinusoidal trajectory with forearm rotation DOF while the control program was rendering a low output impedance (with virtual moment of inertia $I = 0.005kgm^2/°$ and damping $D = 0.08Nms/°$). Movements were performed to track sinusoidal trajectories of frequencies $0.1, 0.2, \ldots 1Hz$. The subject could easily follow the given profiles (Fig.3.31A, B) with a resistance due to inertia and friction shown in Fig.3.31C and Table. 3.4. Note that the movement frequency range of patients using this robot are likely to be limited to $0.5Hz$, where the resistance is less than $0.1N$. For instance, the movement of children affected by cerebral palsy who performed the study described below exhibited a frequency range below $0.4Hz$ in the forearm rotation and below $0.2Hz$ for hand opening/closing.

Dynamic compensation

Fig. 3.32 shows the evolution of the dynamic model parameters (after filter)

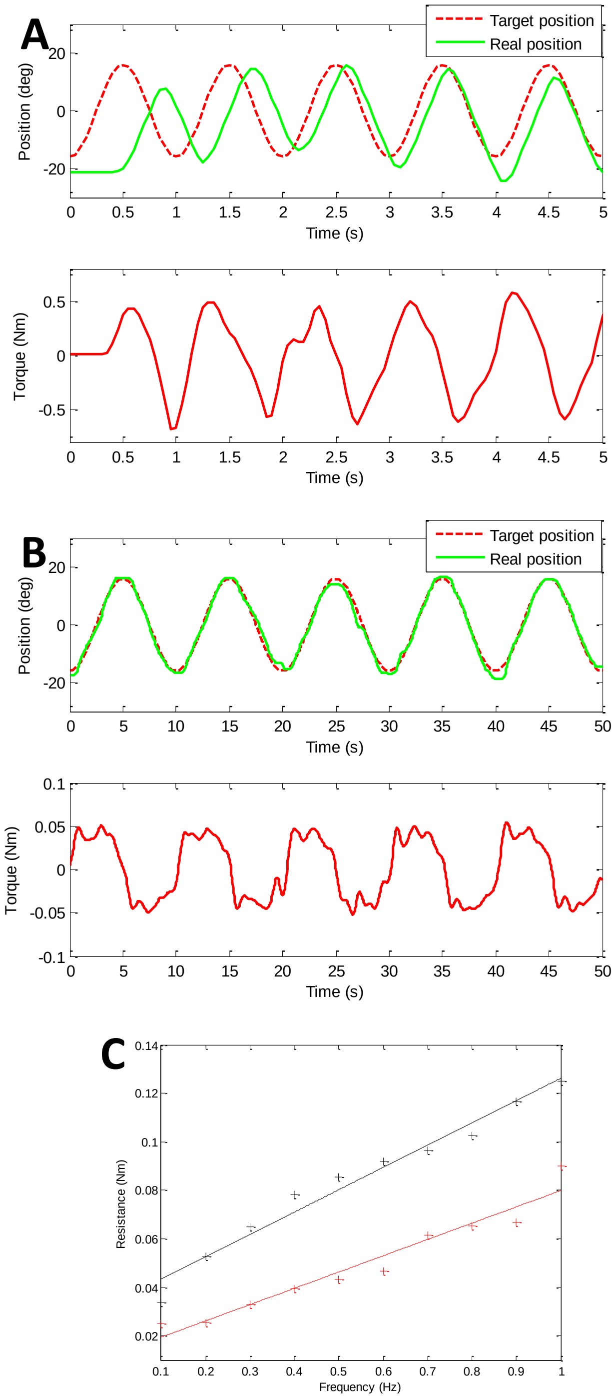

Figure 3.31: The obtained results while a subject was asked to follow predefined profiles with different frequencies. (A) $f = 1Hz$. (B) $f = 0.1Hz$. (C) Residual resistance to sinusoidal movements.

during the identification process ($\eta = 0.0002$). From the figure, it can be seen that the parameters stabilize at certain values as the position error approaching zero value. The final value obtained were $p1 = -0.4123kg/s^2$, $p2 = 1.8792kg * m/s^2$ and $p3 = 1.2763kg * m/s$ (Equ. 3.22).

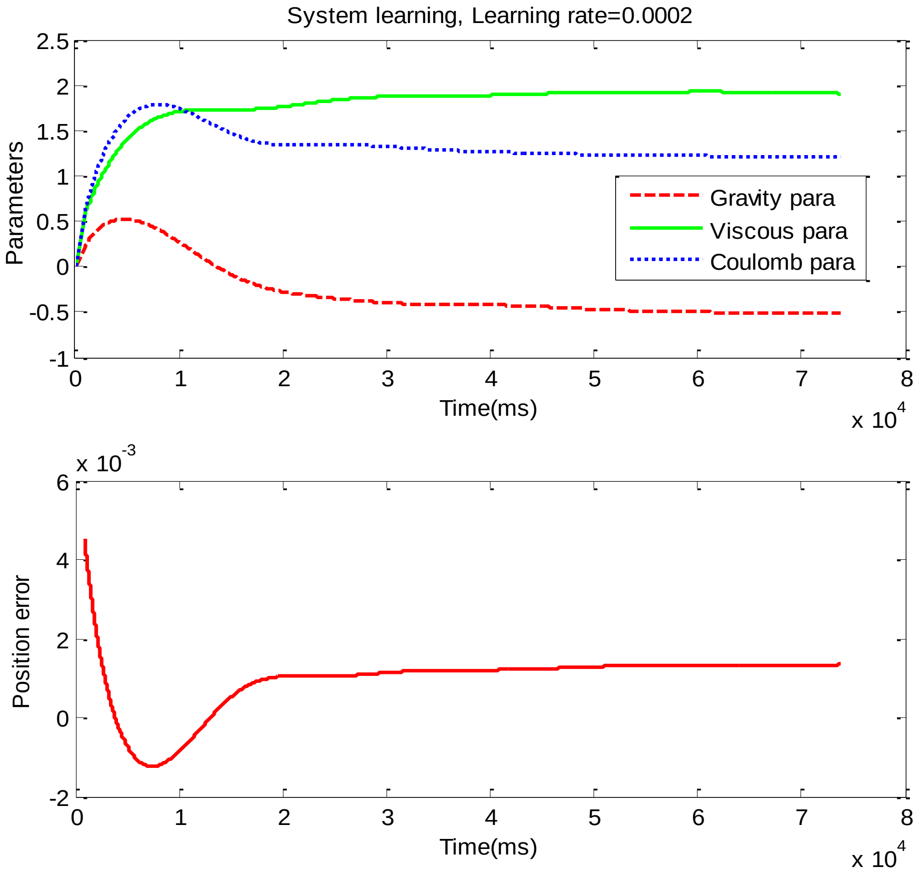

Figure 3.32: Parameters' update during learning: Gravity parameter, $p1 = -0.4123 kg/s^2$; Viscous parameter, $p2 = 1.8792 kg * m/s^2$; Coulomb parameter, $p3 = 1.2763 kg * m/s$.

Fig. 3.33 shows the comparison of velocity tracking error and torques before (FB) and after the dynamic compensation (FF), respectively. The absolute mean velocity tracking error is divided about 10, from 0.0637 rps to 0.0055 rps by the dynamic compensation. In addition, we can see that the feedback control torque is very small and close to zero after the dynamic compensation, i.e. the main control is the feedforward torque. These demonstrates the quality of the dynamic compensation, suggesting more precise motion control can be achieved after dynamic compensation.

Frequency response

To test the effect of feedforward compensation, the bandwidth of closed-loop control was estimated by tracking a $30°/s$ amplitude sinusoidal velocity input trajectory with the forearm rotation axis. Analysing the velocity

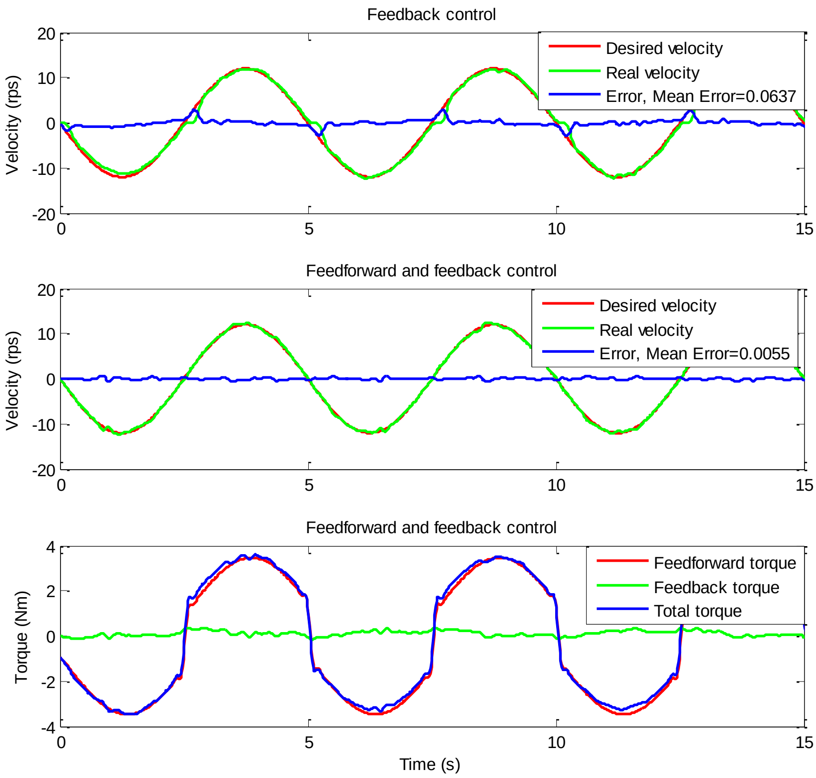

Figure 3.33: Velocity tracking error and torques before and after compensation.

response showed that the dynamic compensation increased the bandwidth from $1.84Hz$ without to $3.9Hz$ (Fig. 3.34). This further demonstrates the quality of the dynamic identification and is sufficient to interact with human movements limited by the 2 Hz bandwidth of muscle mechanics. A similar analysis of the hand opening/closing movement with a $50°/s$ amplitude sinusoidal velocity input exhibited a bandwidth of $3.78Hz$ (Fig. 3.35).

3.8 Summary

In this chapter, we have developed a novel robotic system, reachMAN2, for pediatric upper limb rehabilitation. The robot is specially designed for children and focused on the training of specific functions, which are most often used in performing ADL. The device considers the physical impair-

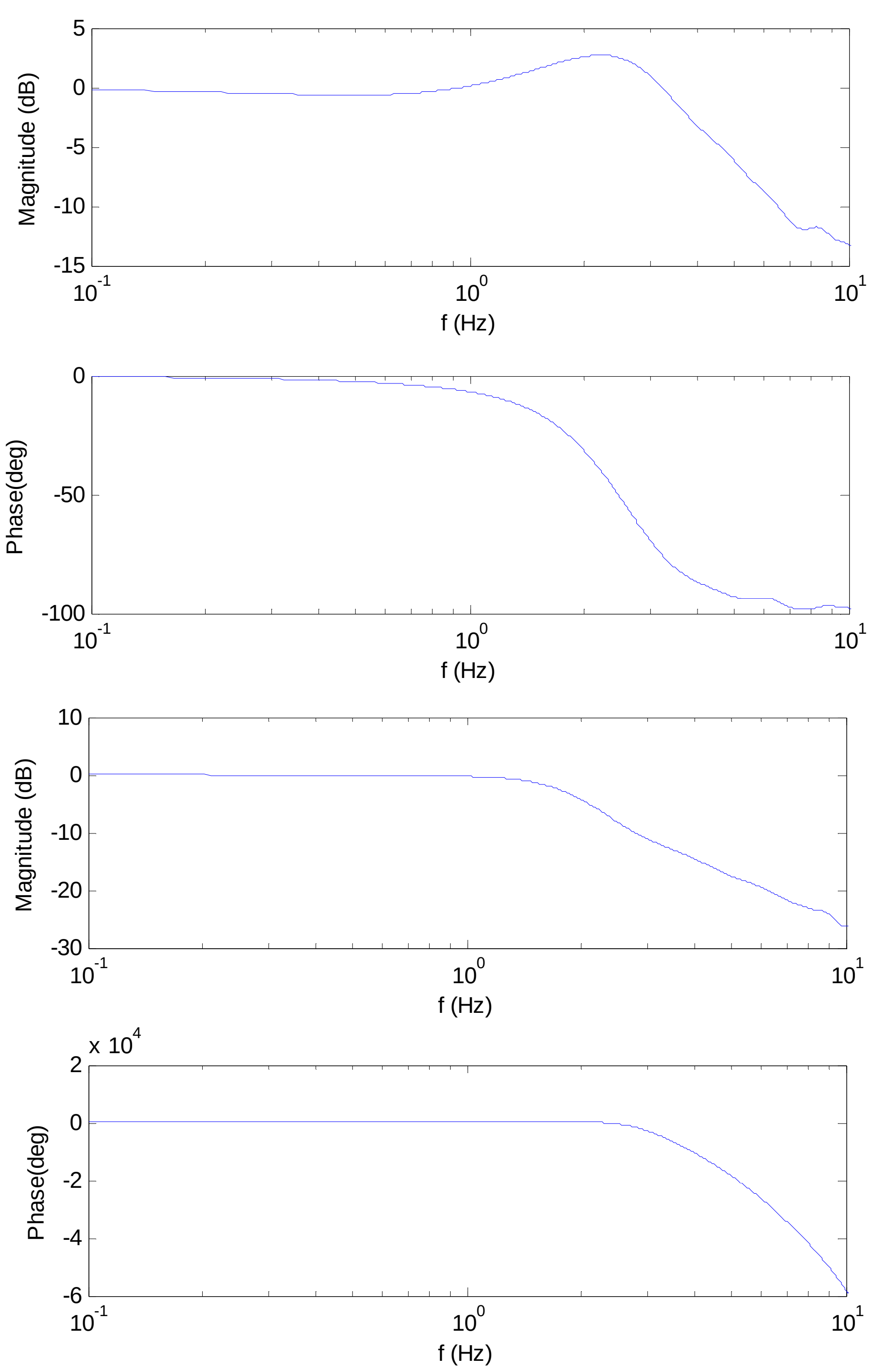

Figure 3.34: The bode plots of the forearm rotation DOF with (top) and without (bottom) dynamic compensation.

ments resulting from CP and the biomechanical properties of the human hand. The innovative cam mechanism improves comfort and avoids back and forth movement of the arm while performing hand opening/closing functions. Different fixtures/handles can be used to train various types of hand prehension such as grasping and pinching. Redundant safety mea-

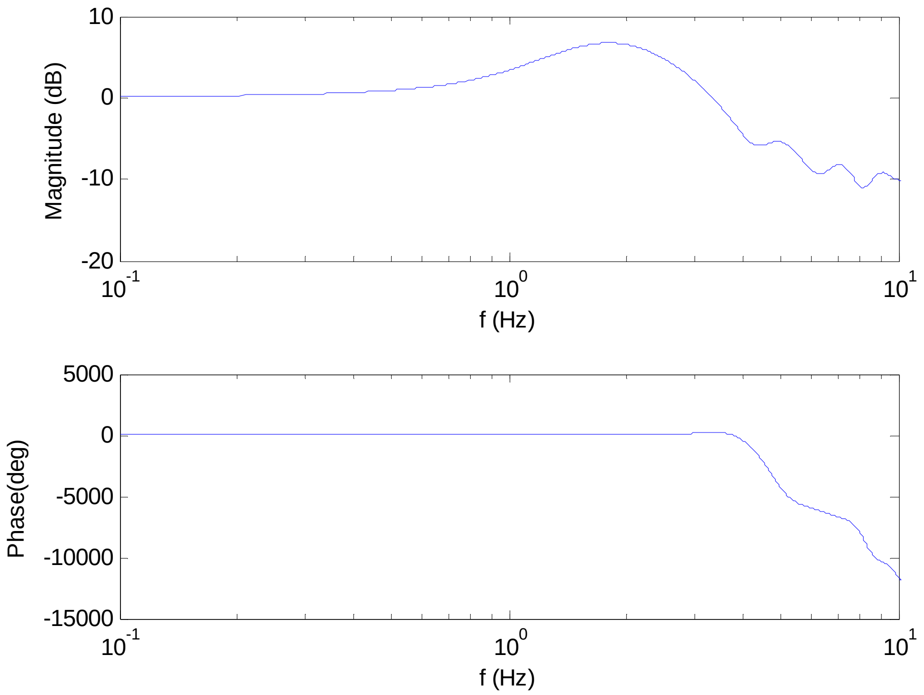

Figure 3.35: The bode plot of the hand opening/closing DOF with the implemented feedback control.

surements were implemented and parameters such as range of motion and force/torque can be adjusted to suit various users.

In contrast to the existing robotic devices for rehabilitation presented in Section 2.4, the developed robotic device is specifically designed for pediatric rehabilitation and can offer therapy for arm, wrist and fingers. With a large range of motion and outputs, the device can adapt to different subjects with various levels of impairment. In particular, the device can offer active training for both opening and closing movements of the pinching exercise, which is very critical for motor learning.

Additionally, the reachMAN2 is a very compact end-effector robotic device and easy to setup. Special attention has been given to the appearance of the robotic device for comfortable and secure interaction.

Chapter 4

The implemented computer games for reachMAN2

4.1 Introduction

Over the past several decades, computer entertainment technology has made significant improvements in both the complexity and realism of games produced. CP children who suffer from various types of impairments is a relatively new group of audience. For the field of rehabilitation, studies have shown that virtual reality games can produce significant motivation to patients (Crosbie et al. [2007]; Roberto et al. [2007]; Loureiro et al. [2004]). In addition, it is well admitted that longer therapeutic sessions produce greater functional outcomes and sustained participation will lead to greater motor recovery over the course of rehabilitation. Compared to rehabilitation systems for adults, special attention should be given to active participation and engagement since children generally only focus on stuff they are interested in and they may refuse to use the robotic system if they feel bored. Therefore, the combination of robot-assisted rehabilitation therapy with appealing computer games is not only a matter of creating entertainment but a real necessity for motor recovery (Flores et al. [2008]). However, developing games for rehabilitation is difficult since it requires skills from both the medical and game design fields (Goude et al. [2007]).

Despite the rapid increase in the number of robotic systems for rehabilitation, the association between the computer games and the overall effectiveness of the rehabilitation system is not fully understood. In particular, there is a significant need for a guide map of the critical factors in designing interactive computer games for CP children rehabilitation.

This chapter presents the analysis of some computer games or virtual reality interfaces used in the principal robotic devices and discusses the strategies and approaches to develop computer games used in the robotic system. Finally, 9 computer games, 3 for each of the exercise, developed for the robotic device are presented.

All the cartoon characters used in this thesis are from the internet.

4.2 Methodology

Interactive computer games used in pediatric rehabilitation should consider from both rehabilitation and children entertainment aspects. The first goal of the computer games should be to realize the functionality of the robotic device and a second goal is to entertain the children users while they are interacting with the robotic device, thus leading to active participation and stimulating motor recovery.

To compile a set of criteria for designing the important game characteristics from the rehabilitation aspect, a review of several virtual reality games used in existing principal rehabilitation device was performed first. The criteria of children entertainment was obtained through reviewing online computer games dedicated to children and discussing with therapists and doctors from NUH, who work closely with CP children.

Combining the two sets of criteria, i.e. rehabilitation and children entertainment criteria, we obtained the criteria used to develop computer games dedicated to pediatric rehabilitation. Three games were implemented to ensure that children from different age groups would enjoy interacting with the developed robotic system.

4.3 Related work

Over the last two decades, many robotic systems for rehabilitation have been developed and various virtual reality interfaces or games were implemented to provide more motivating and interactive human-robot system. In chapter 2, we reviewed the principal existing robotic systems dedicated to children and adults upper limb rehabilitation. In this chapter, the virtual reality games used in these robotic systems were reviewed and analysed to develop the interactive games for the reachMAN2.

4.3.1 Virtual reality games used in robotic systems for adult rehabilitation

Fig. 4.1 A shows an example of the virtual reality interfaces used in ARmin, a novel robot for arm rehabilitation and capable of training the arm movements in 3D plane (Nef and Mihelj [2006]). The user needs to control the position of the virtual hand to catch a ball, which is moving towards the plane of the virtual hand (Nef and Mihelj [2006]). The interface provides the user instruction on the real time position and the target position of his/her hand to guide the movement of the user.

Fig. 4.1 B presents the user interface used in the Haptic Knob, a two degree-of-freedom robotic interface and capable of training forearm supination/pronation and hand opening/closing (Lambercy et al. [2007]). The user has to reduce the size of the image to a predefined target position (white frame Fig.4.1 B) through gradually closing the hand. To that end, the user uses the left bar in the interface and has to follow the (green) reference position throughout the movement. The virtual reality game is simple and easy to understand. However, subjects may feel bored after several trials since the games cannot provide constant novelty to them.

Fig. 4.1 C is the user interface used in the reachMAN (Yeong et al. [2009]), a personal robotic device to train reaching (A), pronation/supination (B), hand opening/closing (C) and combination of reaching and pronation/supination (D). The user has to control the position of the green handle to align target position as indicated by the red handle through the required movement. Similarly, the subjects may feel bored after several trials.

Fig. 4.1 D shows the MIT-MANUS, a 2 DOF robotic device for shoulder-and-elbow therapy (Krebs et al. [2004]). The user interface shows the real time position of the handle and indicates the target position at the beginning of each movement. The user has to move to and from a central target and eight peripheral compass-point targets via movement at the shoulder and elbow joints (Fasoli et al. [2008]). The virtual reality game probably is more interesting compared to the last 3 reviewed games since it takes some time to go through all the possible scenarios.

4.3.2 Virtual reality games used in robotic systems for pediatric rehabilitation

Fig. 4.2 A shows the InMotion2 robot, the commercial version of the 2-DOF robot MIT-MANUS (Masia et al. [2007]) and also the first robotic device used to study the feasibility and effects of robotic therapy in children with

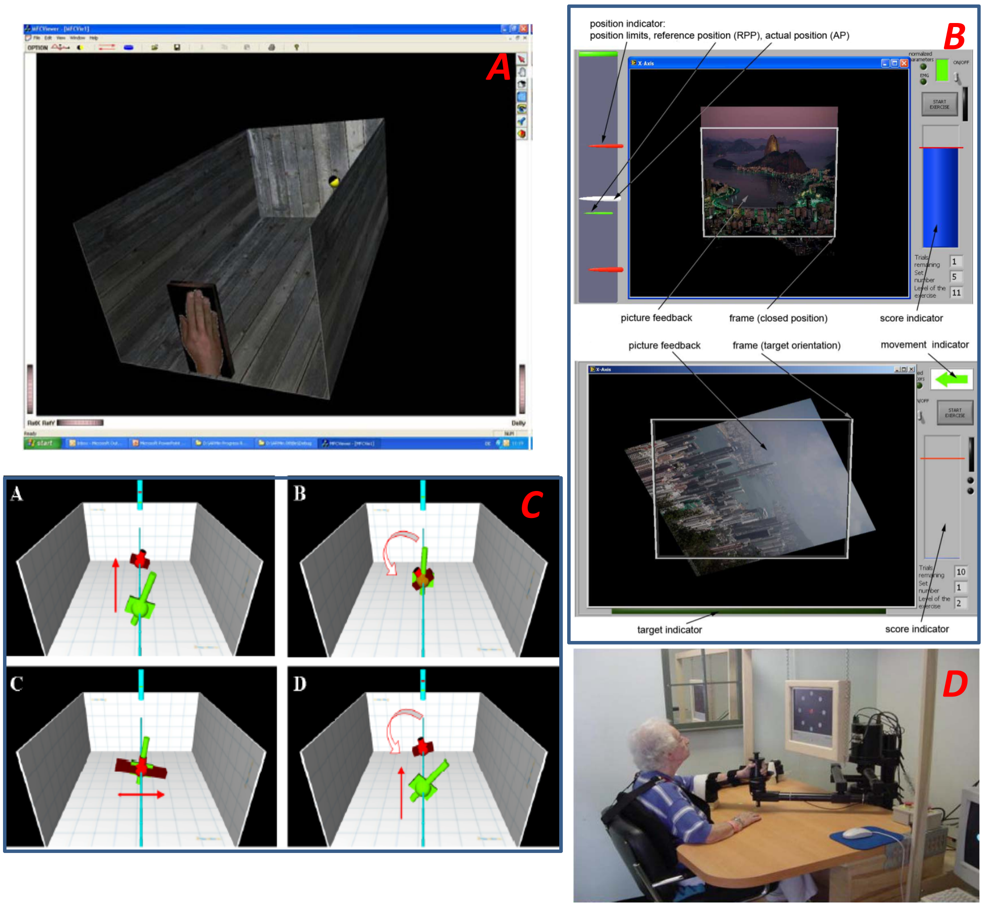

Figure 4.1: Virtual reality games used in robotic systems dedicated to upper-limb rehabilitation for adult. The ARMin (Nef et al. [2007]) (A); The Haptic Knob (Lambercy et al. [2007]) (B); The reachMAN (Yeong et al. [2009]) (C) and the MIT-MANUS (Krebs et al. [2004]) (D).

upper limb hemiplegia (Fasoli et al. [2008]). The user interface, similar to the one used in MIT-MANUS, shows the real time position of the handle and indicates the target position at the beginning of each movement. The user has to move to and from a central target and eight peripheral compass-point targets via movement at the shoulder and elbow joints (Fasoli et al. [2008]).

Fig. 4.2 B presents the interactive computer games used in the NJIT-RAVR (Fluet et al. [2010]), which has 6 DOF and is the combination of the Haptic Master (Van der Linde et al. [2002]) and a ring gimbal. The detailed information of the five interactive computer games are as follows:

- In the bubble explosion game (Fig. 4.2 B(a)), the participant needs

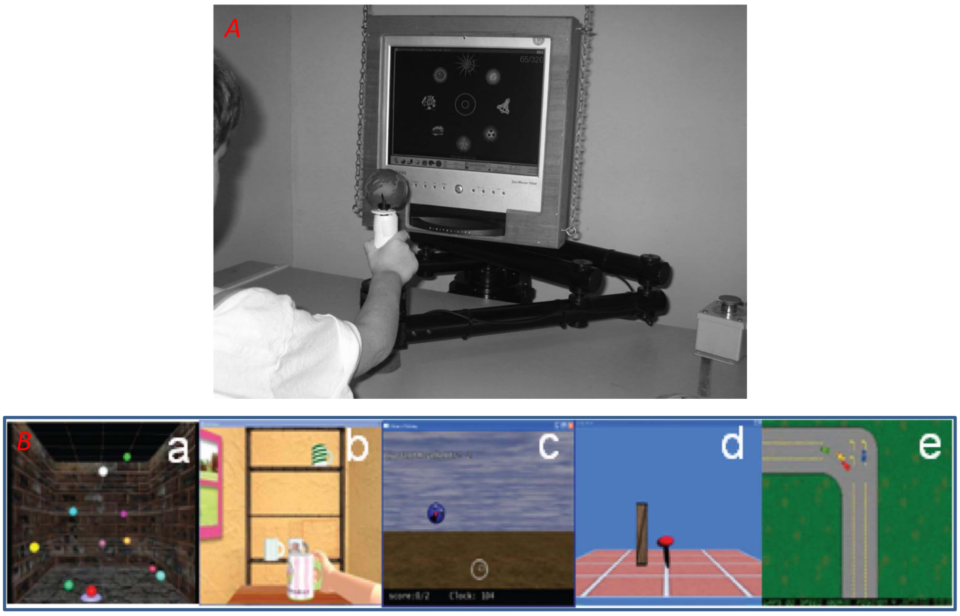

Figure 4.2: Virtual reality games used in robotic systems dedicated to upper-limb rehabilitation for children. The InMotion2 robot (Fasoli et al. [2008]) (A); The NJIT-RAVR (Fluet et al. [2010]) (B).

to control the position of a virtual cursor in a 3D environment to touch a series of 10 rendered bubbles, floating in the 3D space (Fluet et al. [2010]).

- In the cup reach game (Fig. 4.2 B(b)), the user has to use their virtual hand to lift the virtual cup and place it to a target position, indicated by a red square (Fluet et al. [2010]).
- In the falling objects game (Fig. 4.2 B(c)), the participant needs to control the virtual cursor to catch the falling object before it hits the ground (Fluet et al. [2010]).
- In the hammer game (Fig. 4.2 B(d)), the subject can control the position and orientation of the virtual hammer via rotating the forearm. During training, the subject needs to move the hammer to the target, which is shown in the middle of the screen, via repetitive forearm rotation to drive the target into the ground (Fluet et al. [2010]).
- In the car race game (Fig. 4.2 B(e)), the subject uses a slight force ei-

ther forwards or backwards to increase or decrease the speed of the car and controls the direction of the car by forearm pronation/supination movement (Fluet et al. [2010]).

Interestingly, the researchers in the NJIT-RAVR group studied the popularity of the five games among two CP children involved. The result shows the car race game proved to be the most popular simulation with no attention lapses and both agreement that the game was fun. In contrast, the other games did not receive such positive response.

Table 4.1: Properties of the virtual reality games used in the principal existing upper limb rehabilitation robotic devices

Robotic devices	*Target*	*Number of games*	*Evaluated?*
ARMin (Nef et al. [2007])	Adults	3	No
Haptic Knob (Lambercy et al. [2007])	Adults	1	No
reachMAN (Yeong et al. [2009])	Adults	1	No
MIT-MANUS (Krebs et al. [2004])	Adults	1	No
InMotion2 (Masia et al. [2007])	Children	1	No
NJIT-RAVR (Fluet et al. [2010])	Children	5	Yes

4.4 Synthesis

Table 4.1 summarizes some of the properties of the virtual reality games used in the principal existing upper limb rehabilitation robotic devices for adults and children presented in this chapter, it also shows the number of games developed with each robotic device for each type of exercise and whether the effectiveness of the games (i.e. whether they can keep engaging the users throughout a certain period of training) were evaluated or discussed in their publications.

The main conclusions of this review are that many virtual reality games have been developed and implemented with rehabilitation robotic devices dedicated to children and adults. However, most of the games, especially those for adult rehabilitation, are mainly focused on rehabilitation purpose, i.e. effective motor skills' training, to realize the functionalities of the developed robotic devices. In particular, little attention has been paid to the entertainment aspects of the games, which are more important in children rehabilitation compared to adult rehabilitation since children generally only focus on things they are interested in. The study results in Fluet et al. [2010] showed that interesting games lead to fully engagement of the children subjects and longer play time, which promotes motor recovery and skill acquisition. Therefore, special attention should be given to the development of the virtual reality games in rehabilitation robotic devices, especially those dedicated to children.

Table 4.2: Design criteria for children rehabilitation robotic systems

Criteria for rehabilitation	*Criteria for children entertainment*
Meaningful exercises (Exercises)	Simple interface
Appropriate feedback (Feedback)	Various interactive feedback
Adaptable to motor impairments (Adaptability)	Appropriate challenging tasks Constant stimulation/novelty

Through reviewing the virtual reality games used in existing upper limb rehabilitation robotic devices for adults and children, we summarized the rehabilitation criteria of designing virtual reality games for pediatric rehabilitation as shown in Table. 4.2. The criteria of children entertainment criteria of virtual reality games are derived through reviewing the online games for kids[1] and discussion with therapists and doctors from NUH who

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[1] http://www.uptoten.com/kids/kidsgames-home.html

work closely with CP children. The two sets of criteria of developing virtual reality games for children rehabilitation are summarized in Table. 4.2.

4.4.1 Exercises

Generally, there are two types of exercises, active exercises and passive exercises, which are currently used in robot-assisted rehabilitation, with a number of subcategories, e.g. assistive or resistive forces fields. In active exercises, subjects initiate and control the motion. In contrast, in passive exercises, the motion is initiated and controlled by the robot and subjects just follow the movement. Hesse et al. showed that passive training can improve joint and muscle mobility as well as reduce muscle tone (Hesse et al. [2003]).

However, passive exercises controlled by the robotic device may not be sufficient to gain good recovery results. Although passive exercises may improve passive properties of joints and muscles, active exercises initiated and controlled by the subject can build muscle strength and improve muscle coordination, thus leading to correct patterns of muscle activation and coordination (Hogan et al. [2006]).

In addition, motor recovery after CP is believed as a form of motor learning, where the brains relearn how to control the muscles. Rehabilitation is significantly important since children's brains are making continual changes as they grow and mature. Therefore, robot-assisted rehabilitation should focus on active movements where subjects initiate and control the motion to help develop control strategies which are optimal for the specific task (Reinkensmeyer et al. [2004]).

More importantly, task oriented exercises make it easy to understand and identify them with daily activities (Flores et al. [2008]). Our strategy here is the same as the strategy used for the Haptic Knob (Lambercy et al. [2007]), i.e. decomposing complex tasks into several simple subtasks and training them individually, such as pinching a key and turning the key to open the door.

4.4.2 Feedback

Feedback, a common technique used to motivate patients in rehabilitation systems, is used to inform the user how well he/she is performing, how much he/she is improving and motivate the user to continue with the therapy (Flores et al. [2008]). It is also an active part of the therapy, which stimulates motor recovery (Poole [1991]). Generally, there are four main types of feedback methods, i.e. visual, audio, haptic and psychological, used in interactive games for rehabilitation:

- Visual feedback is very often used in robot-assisted rehabilitation systems (Laver et al. [2015]). It is generally easy to understand and relate to the trained task and can suit to the specific needs of the user. Through amplifying subjects' actual performance and enhancing visual-motor coordination, exercises with visual feedback may improve the quality of the therapy (Saposnik et al. [2011]). Moreover, visual feedback can help subjects to go beyond their limits by using visual feedback distortion, i.e. gradually change the visual feedback related to forces or distances without the subject's notice (Weiss et al. [2013]).
- Audio feedback is another type of feedback that can be used in robot-assisted rehabilitation for children. Firstly, background music which children like can be used to increase their interest in the computer games. Secondly, different types of sounds can be used to 'reward' or 'punish' the child if he/she is performing well or bad to motivate the

child to do a good job.

- Haptic feedback is very important for CP children rehabilitation since the resulted motor impairments are often accompanied by sensation and perception problems. Some CP children may have difficulty to detect force or localize their hands in space, which significantly affects their ADL. Haptic feedback such as specific force/torque patterns can stimulate proprioceptive sensors in the skin, joints and muscles to restore sensation of the impaired limb (Lambercy [2009]).
- Psychological feedback refers to information, which could be negative or positive feedback, given to subjects by therapists or robotic devices to assess the performance of the subject. It can be in different forms such as giving a score and commenting on the performance. This information on successful and failed actions allows subjects to adjust and direct their efforts to match the challenge they are facing (Fishbach et al. [2010]).

4.4.3 Adaptability

Adaptability is defined as the ability for the computer games to adapt to different subjects. Motor impairments of CP children vary from one to another. Successful rehabilitation requires that the computer games used with a robotic device is able to adapt to patients' impairment levels (Flores et al. [2008]). Moreover, adaptability is also important for individuals so that the subject can have challenging but not too difficult task after his/her motor skills improve over time.

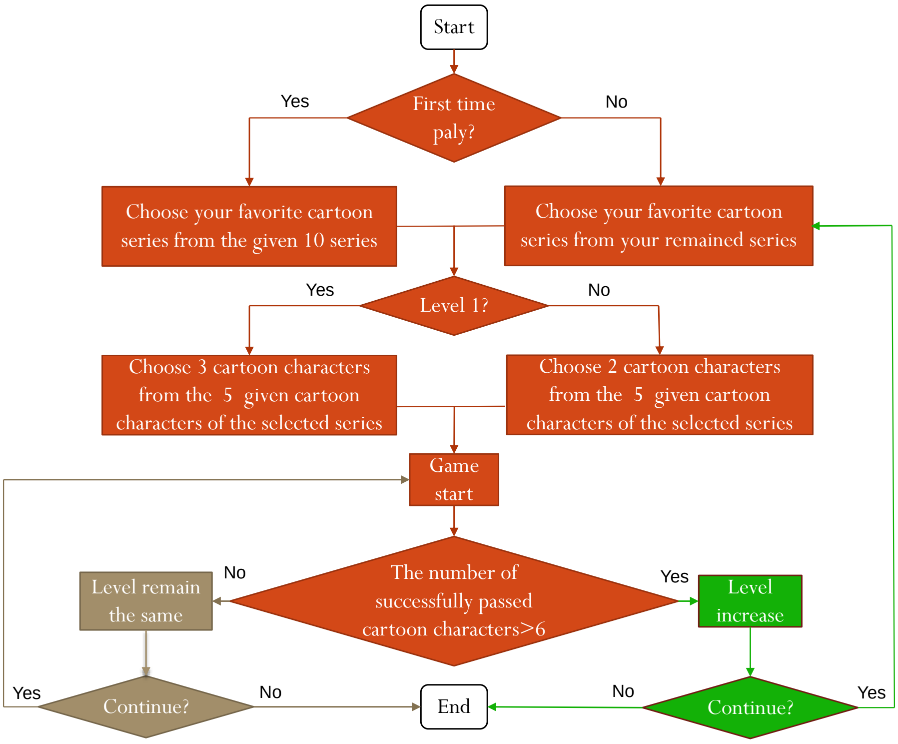


Figure 4.3: The flow chart of the gate game.

4.5 The implemented computer games

Based on the above observations and therapists' opinions on what children like, 9 computer games, 3 for each of the three exercises (pinching, forearm supination/pronation and wrist flexion/extension), have been implemented on the reachMAN2. The detailed information about the 3 games are as follows.

4.5.1 Gate game

The first game is the gate game as shown in Fig. 4.4. The detailed logic of the gate game is as shown in Fig. 4.3. If the child plays it for the first time, he/she can choose his/her favourite series of cartoon characters from a list of 10 series of cartoon characters, which are currently very popular among children, as shown in Fig. 4.5. Then he/she will need to choose 3 cartoon characters from a list of 5 cartoon characters which belong to

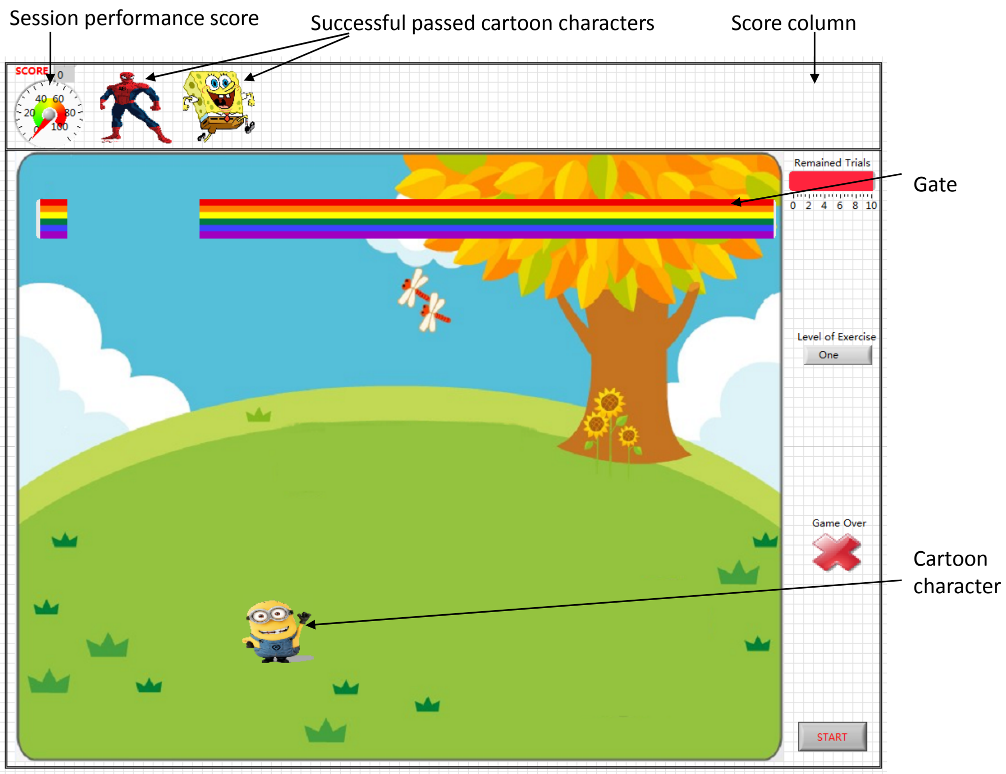


Figure 4.4: User interface of the gate game at the beginning of one trial.

his/her favourite series as his/her collection. An example of the 5 cartoon characters is shown in Fig. 4.6. After these selections, the game will start. One of the cartoon characters from the collection will appear at the bottom and a gate with a hole will be descending at a certain speed from the top of the game interface as shown in Fig. 4.4. The subject needs to control the horizontal position of the cartoon character, which linearly moves along with the angular displacement of the robotic device, by either pinching, forearm supination/pronation or wrist flexion/extension movements to go through the hole in the gate. If the cartoon character passes the hole successfully, a score (S_i, i is the trial number) from 0 to 100 together with a smiley face as shown in Fig. 4.7 would appear to assess the movement precision of the trial. The calculation of the score is according to the horizontal position of the cartoon character (P_c) relative to the horizontal position of the hole (P_h) where the cartoon character passing through the hole as shown in the following equation (S_h is the size of the hole):

$$S_i = 100 - 2\left|\frac{P_c - P_h}{S_h}\right| \tag{4.1}$$

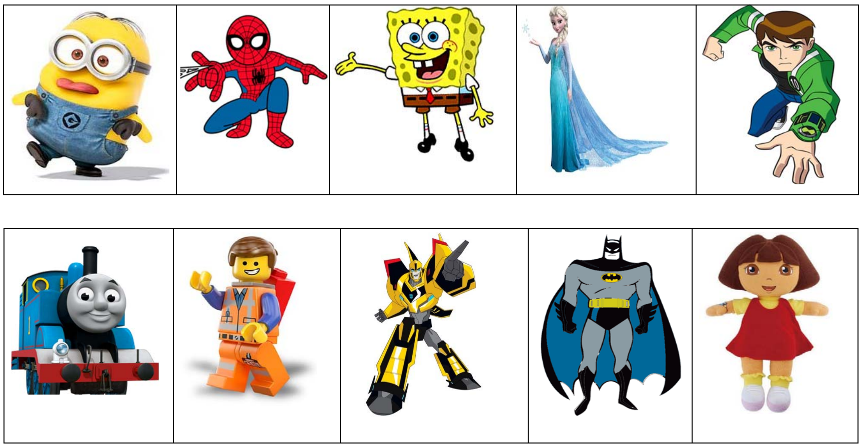


Figure 4.5: The list of 10 series of cartoon characters.

In addition, the cartoon character will appear in the score column and a new different cartoon character from the collection will show up as a reward and a new different gate will be descending from the top of the game interface for the next trial. If the subject fails, a sad face will appear as a kind of negative feedback, and both the cartoon character and the collection will not change and a new different gate will be descending from the top of the game interface again for the next trial. This is one of the 10 trials in one set. The score (S) in the score column (Fig. 4.4) is to assess the movement precision of all the 10 trials in one set and calculated as shown in the following equation:

$$S = \sum_{i=1}^{10} \frac{S_i}{10} \tag{4.2}$$

If the child manages to get at least 7 cartoon characters (the number of successful trials) in the score column after one set of trials, the difficulty level of the game will be increased automatically, which means the speed of

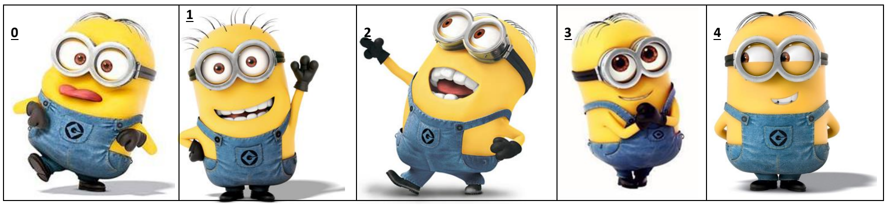


Figure 4.6: An example of 5 cartoon characters.

the gate descending from the top of the game interface will be faster, the size of the hole in the gate will be smaller and the force/torque required to move the cartoon character will be increased. In addition, the subject can choose another two cartoon characters from his/her favourite series of the remained series of cartoon characters, which would be included in his/her collection as a reward. So the subject would have more cartoon characters in his/her collection at higher levels, and the goal is to motivate the subject to move to the higher levels. If the subject fails in one set of trials (less than 7 cartoon characters in the score column), the difficulty level of the game will remain the same and no new cartoon characters will be included in his/her collection.

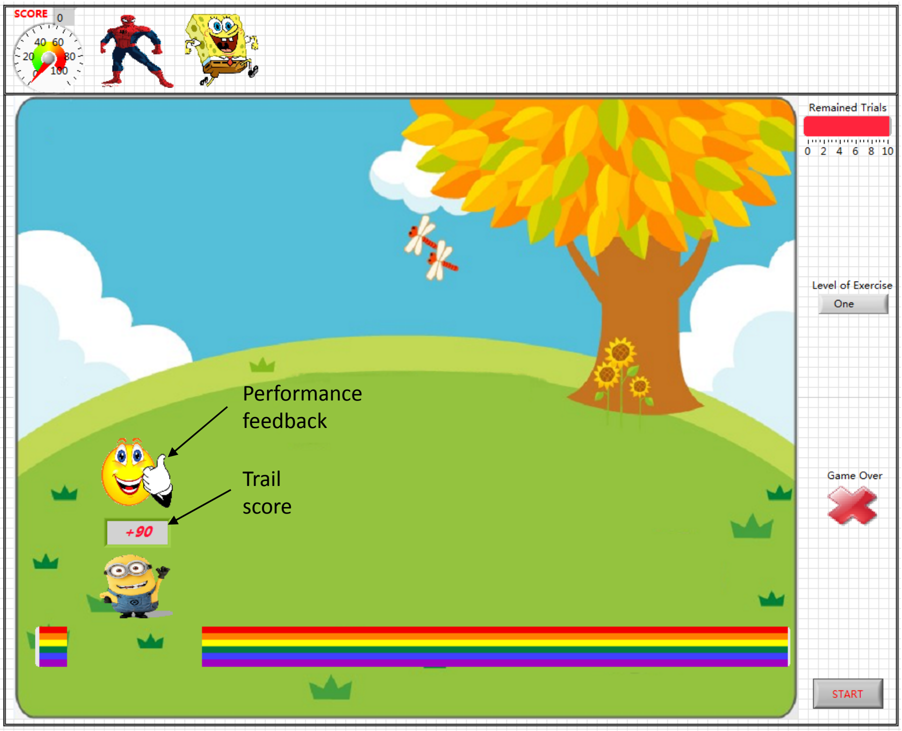


Figure 4.7: User interface of the gate game at the end of one trial.

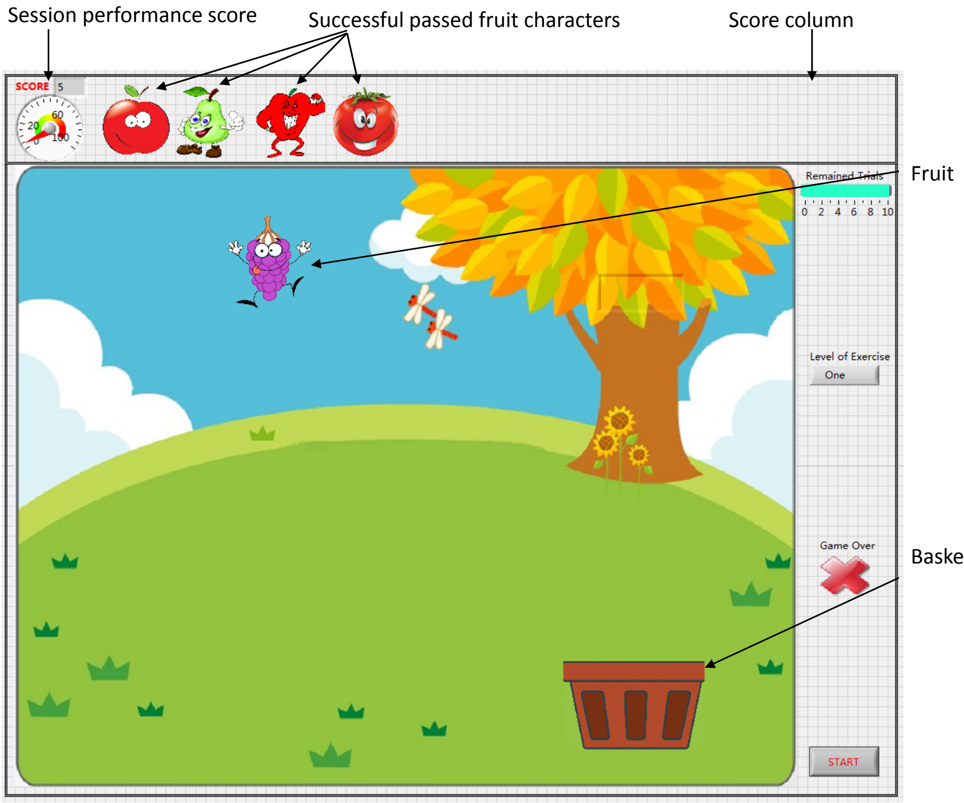


Figure 4.8: User interface of the fruit game at the beginning of one trial.

4.5.2 Fruit game

The second game is the fruit game as shown in Fig. 4.8. At first, the child can choose his/her favourite one type of fruit characters from a list of 10 types of fruit characters, which are commonly seen in daily living, as shown in Fig. 4.9. Then he/she will need to choose 3 fruit characters from a list of 5 fruit characters, which all belong to his/her chosen favourite type, as his/her collection. An example of the 5 fruit characters is shown in Fig. 4.10. After all these are finished, the game will start. One of the fruit characters from the collection will be descending at a certain speed from the top of the game interface as shown in Fig. 4.8. The subject needs to control the horizontal position of the basket (Fig. 4.8), which linearly moves along with the angular displacement of the robotic device, by either pinching, forearm supination/pronation or wrist flexion/extension to catch the falling fruit. If the basket catches the fruit character successfully, a score (S_i, i is the trial number) from 0 to 100 together with a smiley face as shown in Fig. 4.11 will be given to assess the movement precision of the trial. The calculation of the score is according to the horizontal position of the fruit character (P_c) relative to the horizontal position of the basket P_h where the fruit character falls into the basket as shown in the following equation (S_h is the size of the basket):

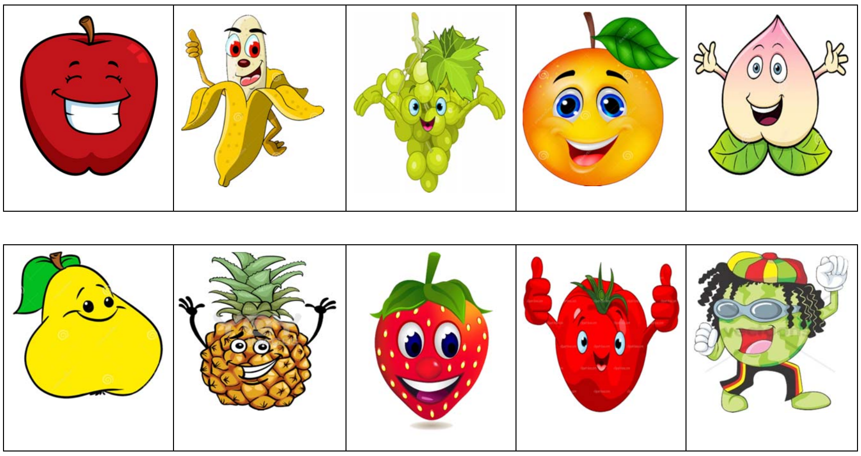


Figure 4.9: The list of 10 types of fruits characters.

$$S_i = 100 - 2\left|\frac{P_c - P_h}{S_h}\right| \tag{4.3}$$

In addition, the fruit character will show up in the score column and a new different basket will appear and a new different fruit from the collection will come down from the top for the next trial. If the subject fails, a sad face will appear as a kind of negative feedback and both the fruit character and the collection will not change. The same fruit character will come down from the top again for the next trial. This is one of the 10 trials in one set. The score (S) in the score column (Fig. 4.8) is to assess the movement precision of all the 10 trials in one set and calculated as shown in the following equation:

$$S = \sum_{i=1}^{10} \frac{S_i}{10} \tag{4.4}$$

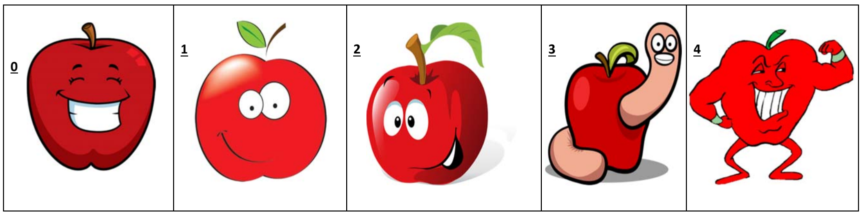
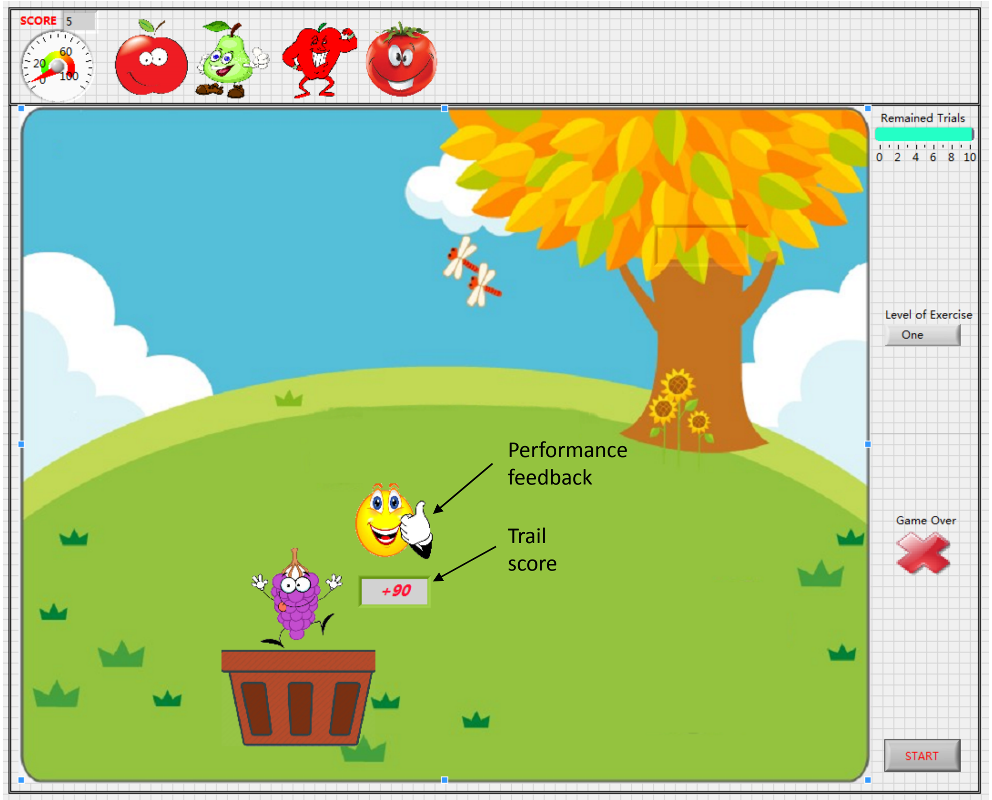


Figure 4.10: An example of 5 fruit characters.

If the child manages to get at least 7 fruit characters (the number of successful trials) in the score column after one set of trials, the difficulty level of the game will be increased automatically, which means the speed of the fruit character coming down will be faster and the force/torque needed to move the basket will be larger. In addition, the child can choose another two fruit characters from his/her favourite type of the remained types of fruit characters, which would be included in his/her collection as a reward. So the subject would have more fruit characters at higher levels. If the subject fails in one set of trials, the level of difficulty of the game will remain the same and no new fruit characters will be included in his/her collection.


SCORE 5

Level of Exercise One

Figure 4.11: User interface of the fruit game at the end of one trial.

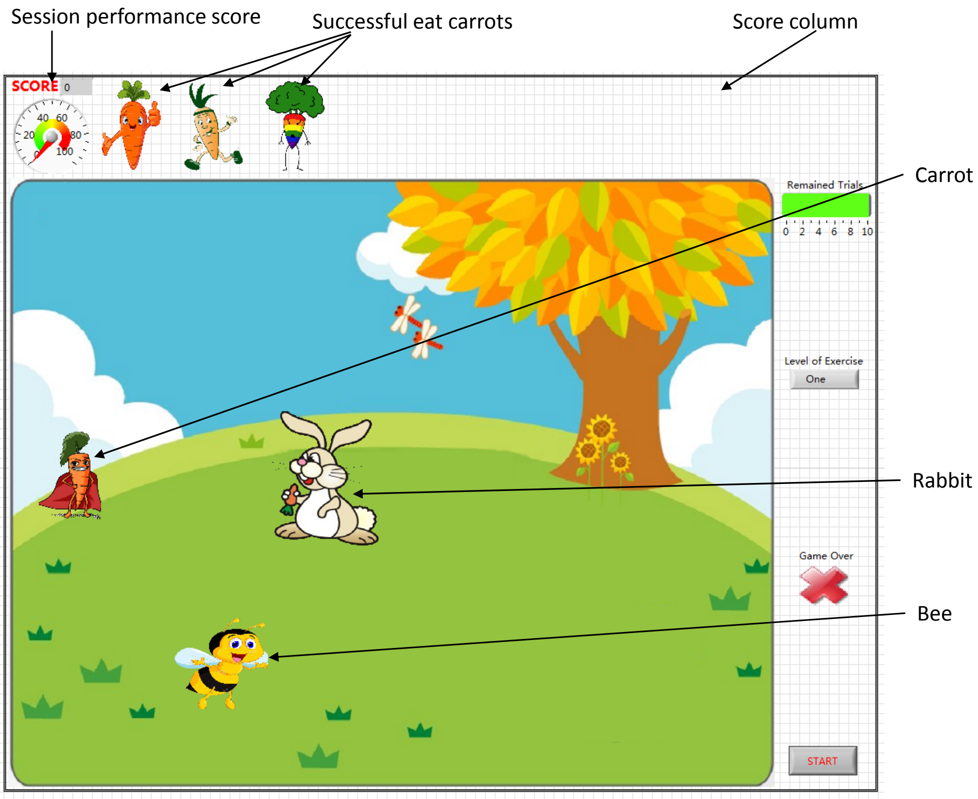


Figure 4.12: User interface of the rabbit game at the beginning of one trial.

4.5.3 Rabbit and fish games

The third and also the final game is the rabbit and fish games. Here we use rabbit game as an example (Fig. 4.12) since they have the same logic (level 1 to 5 is the rabbit game, level 6 to 10 is the fish game). At first, the child can choose his/her favourite three carrot characters from a list of 5 carrot characters (Fig. 4.13) as his/her collection. Then the game will start. One of the carrot characters from the collection will appear at either left side or right side of the rabbit as shown in Fig. 4.12. The subject needs to control the horizontal position of the rabbit, which linearly moves along with the angular displacement of the robot, by either pinching, forearm supination/pronation or wrist flexion/extension to eat the carrot without being struck by the bee which keeps moving up and down in the horizontal middle position of the carrot and the rabbit (Fig. 4.12). If the rabbit successfully eats the carrot character without being struck by the bee, a score (S_i, i is the trial number) from 0 to 100 together with a smiley face as shown in Fig. 4.14 will appear to assess the movement rapidity of the subject for the trial. The calculation of the score is according to the time (t_i) used by the subjects to complete the trial. The equation is as follows (L is the level of the exercise.):

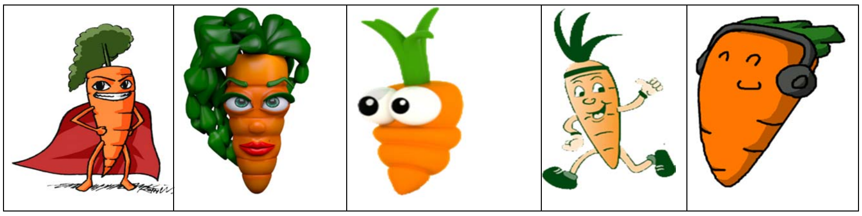


Figure 4.13: The list of 5 types of fruits carrots.

$$S(t)_i = \begin{cases} 100 & 0 \le t_i < \text{4-0.3L} \\ 50(6 - 0.3L - t_i) & \text{4-0.3L} \le t_i \le \text{6-0.3L} \\ 0 & \text{6-0.3L} < t_i \end{cases} \tag{4.5}$$

Therefore, at higher levels of the exercise, a shorter time is allowed to finish the task.

In addition, the carrot character will show up in the score column and a new different carrot character from the collection will appear for the next trial. If the subject fails, a sad face will appear as a kind of negative feedback and both the carrot character and the collection will not change. The same carrot character will appear in a different position for the next trial. This is one of the 10 trials in one set. The score (S) in the score column (Fig. 4.12) is to assess the movement rapidity of all the 10 trials in one set and calculated as shown in the following equation:

$$S = \sum_{i=1}^{10} \frac{S(t)_i}{10} \tag{4.6}$$

If the child manages to get at least 7 carrot characters (the number of suc-

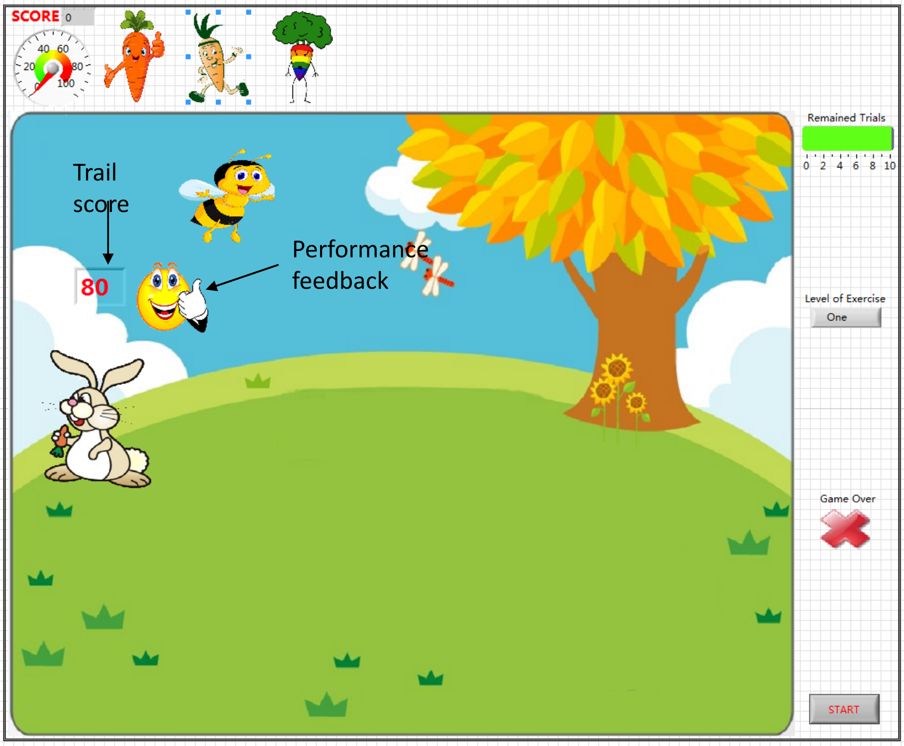


Figure 4.14: User interface of the rabbit game at the end of one trial.

cessful trials) at the score column after one set of trials, the difficulty level of the game will be increased automatically, which means the moving speed of the bee will be faster, the force/torque needed to move the basket will be increased and the time allowed to finish the trial will be decreased. In addition, the child can choose another two carrot characters from the next available 5 carrot characters, which would be included in his/her collection as a reward. So the subject would have more carrot characters at higher levels. If the subject fails in one set of trials, the difficulty level of the game will remain the same and no new carrot characters will be included in his/her collection.

After level 5, the rabbit game will change to fish game and the difference is: the carrot, bee and rabbit change to shrimp, shark and fish respectively. The logic of the fish game is the same as the rabbit game.

4.5.4 Discussion

Passive exercises may reduce spasticity and increase ROM. However, active exercises initiated and controlled by the subject can build muscle strength and improve muscle coordination, thus stimulating motor recovery. Furthermore, motor recovery after CP is believed as a form of motor learning, where the brain relearns how to control the muscles. Therefore, robot-assisted rehabilitation should focus on active movements where subjects initiate and control the motion to help develop control strategies which are optimal for the specific task (Reinkensmeyer et al. [2004]).

Interactive computer game is important in robot-assisted rehabilitation to increase motivation and participation of the subject, thus facilitating skill acquisition. To develop motivating computer games, various types of feedback methods, such as visual, audio, haptic and psychological, should be used.

Based on current feedback techniques used in computer games for rehabilitation and advices from therapists, 9 games, 3 games for each of the three exercises, i.e. pinching, forearm supination/pronation as well as wrist flexion/extension, were implemented. With some modifications, each of the 3 games can be used for any of the 3 exercises. For example, the gate game for wrist flexion/extension and forearm supination/pronation exercises are roughly the same. However, the gate game for pinching exercise is slightly different, with the gate moving from right to left and the cartoon character linearly moving up and down along with the angular displacement of the robotic device in order to associate with the specific exercise more naturally.

In addition, the 3 games for the exercises aim to improve different aspects of the motion control for the subject. For example, in the gate game, the subject needs to control the cartoon character more accurately to successfully pass the hole at higher difficulty levels of the game due to the smaller hole size. In the rabbit and fish games, the subject needs to complete the trial within a shorter time at higher difficulty levels.

Figure 4.15: Different feedbacks after one set of trials.

Different feedbacks were given to the user after he/she finishes one set of trials according to the number of successful trials he gets. Fig. 4.15 shows the feedbacks used after the user completes one set of trials. From left to right, the scores of the four feedbacks are from 1 to 3, 4 to 6, 7 to 8 and 9 to 10, respectively.

Fig. 4.16 shows the various types of feedbacks used in the reachMAN2. Feedback can help realize a task by interacting with the user and increase the active participation, thus stimulating motor recovery (Poole [1991]).

4.6 Summary

In this chapter, we reviewed some of the computer games or virtual reality interfaces used in the principal robotic devices for rehabilitation. We found that these virtual reality games are mainly designed to realize the functionality of the developed hardware. However, careful attention must be given when designing the computer games for pediatric rehabilitation system to incorporate motivation for active participation. Reviewing existing virtual reality games and the online games dedicated to children, we developed the design criteria from rehabilitation and children entertainment aspects for games dedicated to pediatric rehabilitation.

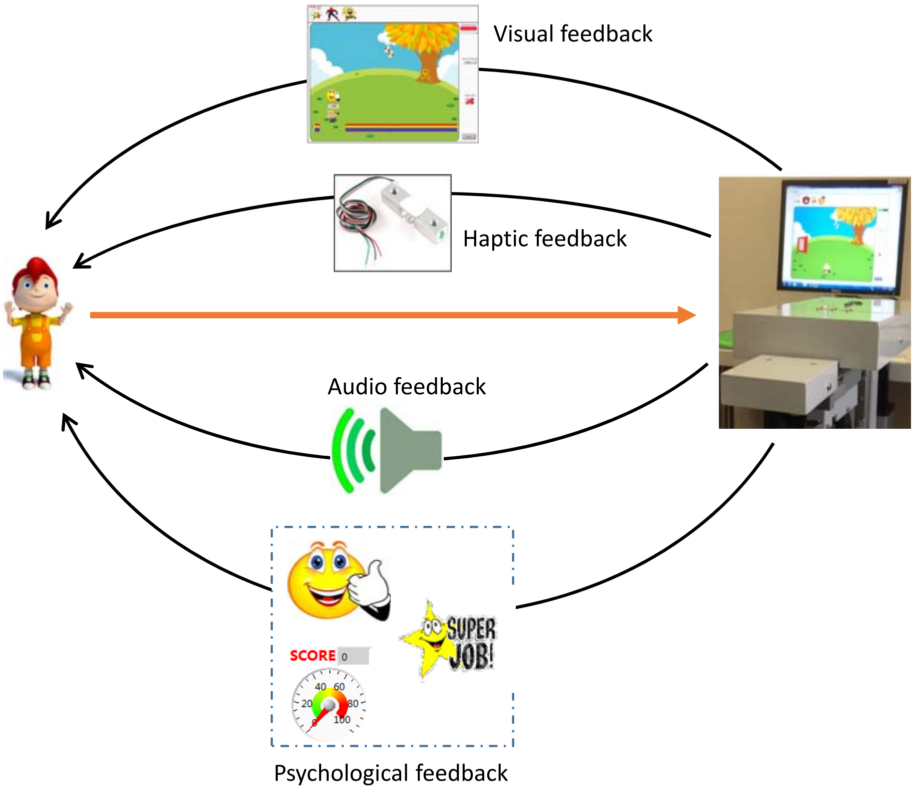


Figure 4.16: Feedback methods implemented on the reachMAN2.

According to the developed design criteria, active exercises were first selected in designing the computer games since active exercises initiated and controlled by the subject can build muscle strength and improve muscle coordination, thus leading to correct patterns of muscle activation and coordination (Reinkensmeyer et al. [2004]). Various feedback methods, audio, video, haptic and psychological feedback, which are commonly used in the virtual reality games dedicated to rehabilitation, were reviewed and selected in designing the computer games.

Finally, 3 computer games aimed to train different aspects of motion control for each exercise (pinching, forearm supination/pronation and wrist flexion/extension) were developed. Adaptable difficulty levels make the robotic system capable of being used by patients with different impairment levels. Various feedback and reward methods were employed to interact with children while using the robotic system and interesting cartoon characters, fruits and animals, which are very popular among children, were used to increase the attraction of the games.

Chapter 5

Pilot study

5.1 Introduction

It is commonly admitted that active participation in adult rehabilitation programs increases the effectiveness of therapy, thus promoting motor recovery and skill acquisition. To increase subjects' participation and engagement, virtual reality games have been used and implemented with robotic systems dedicated to adult rehabilitation. Compared to adult rehabilitation systems, special attention should be given to active participation and engagement for children since they generally only focus on things they are interested in and they may refuse to use the robotic system if they feel bored. In particular, studies on pediatric rehabilitation has shown that appealing games can increase attention and achieve longer therapy time (Fluet et al. [2010]).

Human-Robot Interaction (HRI) is a field of study that addresses the design, understanding as well as evaluation of robotic systems, which involves robotic systems and humans interacting via communication (Goodrich and Schultz [2007]). In this chapter, we evaluated our developed robotic system reachMAN2 based on HRI.

An accurate evaluation not only shows the performance, such as the robustness, usability and automaticity, of the developed robotic system, it also provides feedback information from the direct users and the indirect users to help to design more satisfactory robotic systems. A pilot study, which tests the robotic system with its target users directly in real application environments or lab environment, is a feasible and popular method to achieve effective evaluation results. This method has been used repeatedly in many HRI systems evaluation processes (Wada and Shibata [2007]; Kozima et al. [2009]; Marti and Giusti [2010]).

The first goal of the pilot study is to evaluate whether the children feel comfortable while placing their arms or hands on the robot to interact with it and whether the robot is suitable to be used by them. The second goal is to see whether the children like the developed computer games and remain engaged throughout a 60-minute robotic test, which is often used in clinical studies. The third goal is to collect the parents' opinions on the reachMAN2 system. These useful feedback information from the parents and children would be used to improve the current functions of the robotic system and guide future development of robotic systems dedicated to pediatric rehabilitation.

This chapter is organized as follows. Section 5.2 introduces the methods used to evaluate the performance of the robotic system. Section 5.3 describes the results. Section 5.4 concludes this chapter.

5.2 Methods

5.2.1 Subjects

Seven CP children (aged from 5 to 10 years old; 1 female and 6 males) participated in the one-hour pilot study. They are all able to understand the instructions on how to use the robotic device and have no visual or hearing impairments. Table 6.1 summarizes some of the information of the 7 CP children who participated in the pilot study. The study were conducted at the Rehabilitation Centre of NUH, where the robotic system would be used for the clinical study.

Table 5.1: Information for the 7 CP children involved in the pilot study

subject	*gender*	*age*	*affected hand*	*dominant hand*
P1	M	5	left	right
P2	M	6	right	left
P3	M	8	right	left
P4	F	10	right	left
P5	M	7	right	left
P6	M	5	left	right
P7	M	10	right	left

5.2.2 Exercises

The subjects were asked to perform 3 exercises, i.e. pinching, forearm supination/pronation and wrist flexion/extension individually. The detailed information about the 3 exercises are as follows:

- In the pinching exercise, the subjects started with hand closed and had to open or close the handle with the thumb and index finger to play the games described in the last chapter. Both the opening and closing parts of the exercise are active, i.e. the subject initiates and controls the motion of the exercise.

- In the forearm supination/pronation exercise, the subjects started with forearm rotation at neutral position (angle = 0°) and had to rotate the device counter-clockwise or clockwise direction to play the games described in the last chapter.
- In the wrist flexion/extension exercise, the patients started with normal wrist position and rotated the device clockwise or counter-clockwise direction to interact with the games described in the last chapter.

5.2.3 Protocol

The subjects tried the system for about 60 minutes under the guidance and monitoring by their parents and a research assistant to ensure that they continue to be engaged with the task safely. All of them started with the pinching exercise followed by forearm supination/pronation, then by wrist flexion/extension exercise. Any of the 3 games described in chapter 4 can be associated with each of the exercise. However, each subject must go through all the 3 exercises and 3 games during the 60-minute robotic test. All subjects were informed that frequent breaks were allowed when they feel tired or bored prior to the test and the number of breaks would be used as a kind of measurement on whether the games are appealing enough to engage the children throughout the 60-minute evaluation. A two-minute rest break was given to all subjects between each type of exercise.

The subjects sat comfortably either on a chair provided by NUH or their own wheelchairs and the impaired hand rested on the arm supports (Fig. 5.1). They all started from level 1 of the interactive games and then the computer games adapted to the performance of the subjects during test once they pass the requirements to increase difficulty level of the game.

Figure 5.1: Testing situation of the pilot study.

5.2.4 Evaluation

To effectively evaluate the performance of the reachMAN2 system including the hardware and the interactive games, the questionnaires for children and their parents were prepared separately. The questionnaires for the children were designed to assess the children's feelings on the overall system, computer games and whether they feel comfortable while interacting with the robot. The questionnaires for parents were used to evaluate parents' opinions on the developed computer games. The questions on the two questionnaires were based on a 5-point Likert scale and the parents and children could give some suggestions if they want. The research assistant involved and the parents explained the questionnaire to the children. Table 5.2 and 5.3 list the questions used in the two questionnaires.

The answers to the questions in the questionnaires can reflect the direct attitudes to the robot system from the children and their parents. For

Table 5.2: The questions used in the questionnaire for children

Question 1	Do you like the computer games overall?
Answer	do not like at all; do not like; normal; like; like very much
Question 2	Which game do you like the most?
Answer	gate game; fruit game; rabbit and fish games; none of above
Question 3	Do you feel comfortable while using the robotic device?
Answer	very uncomfortable; uncomfortable; normal; comfortable; very comfortable
Question 4	How do you find the appearance of the robotic system including the robot hardware and the games?
Answer	very scary; scary; normal; appealing; very appealing

Table 5.3: The questions used in the questionnaire for parents

Question 1	Do you think your child likes the developed computer games?
Answer	does not like at all; does not like; normal; likes; likes very much

example, whether they like the developed computer games or the robotic system and whether they feel comfortable while using the robotic device. Together with their suggestions, we would know how to improve the current robotic system and help our future development.

In addition to using questionnaires, whose results are normally subjective, the 60-minute tests were recorded by a video camera to obtain more objective evaluations. Through the facial expressions, body gestures and verbal behaviors of the children in videos, we can have a more objective and detailed information on the children's feeling to the robotic system, especially the computer games. This behavior analysis method has been commonly used in HRI field and also widely used in psychology to study human social interaction (Niculescu et al. [2010]).

5.3 Results

5.3.1 Results from questionnaire analysis

Figure 5.2 to 5.5 show the statistical results of each question in the questionnaire according to the children's responses. The score values in the figures indicate the number of votes for that specific category from the children and hence the maximal value should be 7, the total number of children involved in the study.

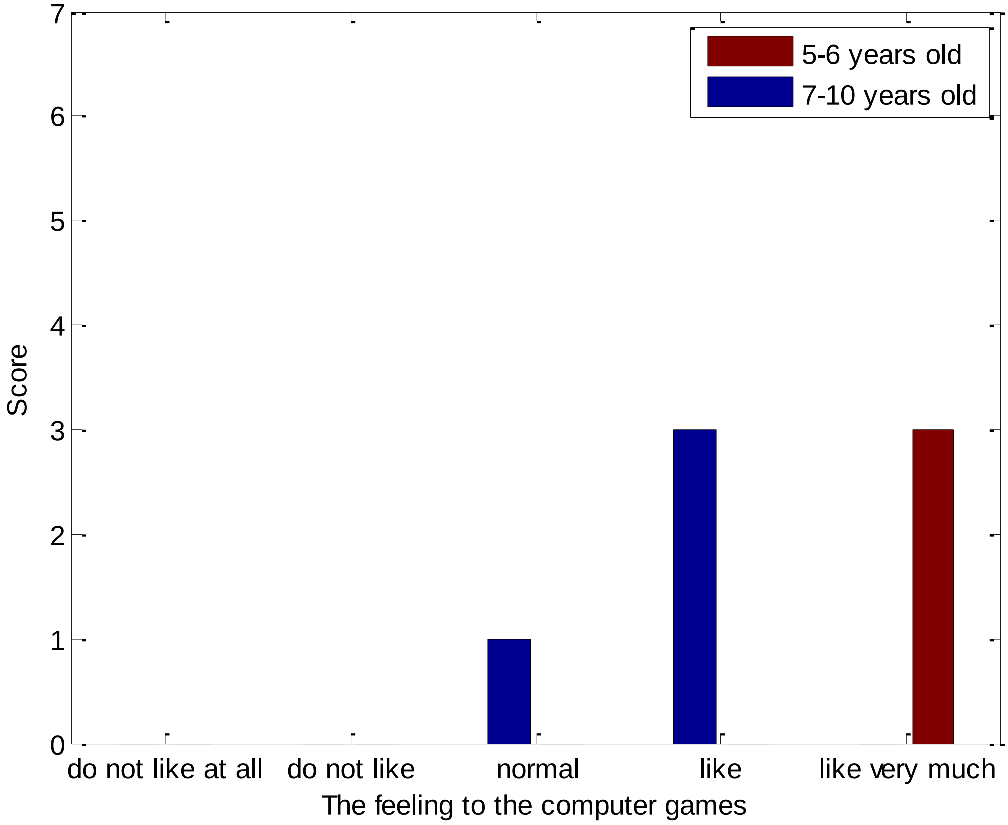


Figure 5.2: The statistical result of Question 1 in Table 5.2.

Figure 5.2 presents the responses from the children to Question 1 in Table 5.2. The goal of designing this question is to see whether the children like the implemented computer games such that they can be engaged in the robotic test. Two different colours were used to indicate different age groups. Brown and dark blue were used to indicate children at 5 to 6 years old and children at 7 to 10 years old respectively. From the figure, we can see that all the 7 children like the computer games. Interestingly, younger children like the computer games more compared to older ones, probably because cartoon characters are more popular among younger children.

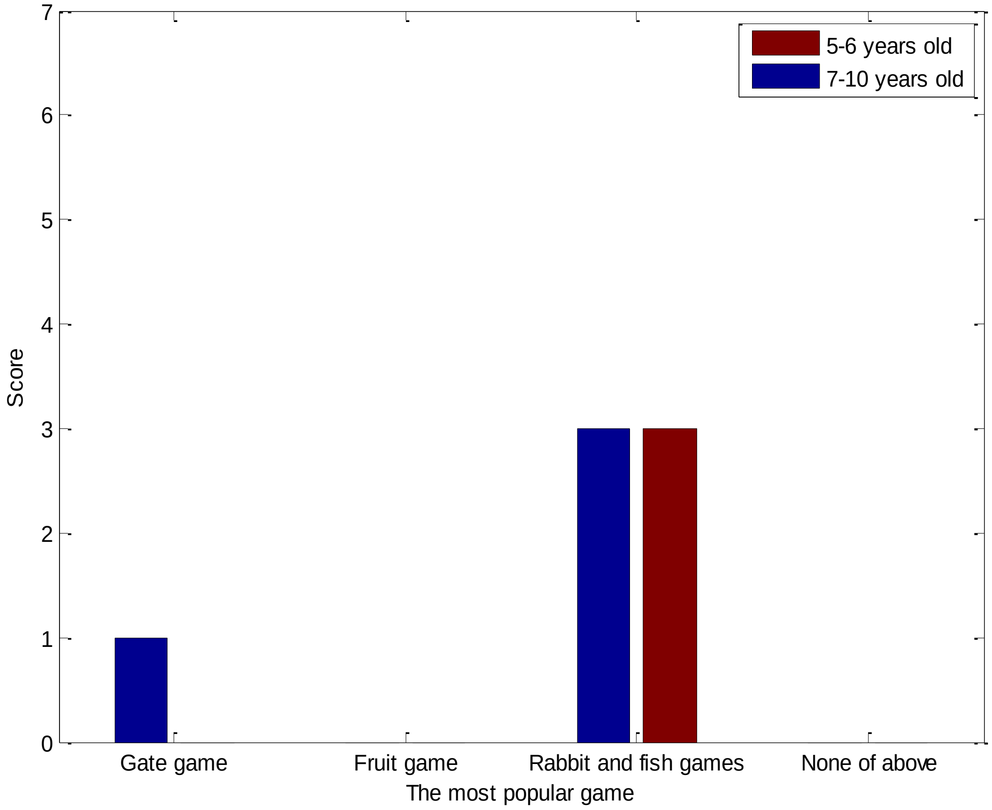


Figure 5.3: The statistical result of Question 2 in Table 5.2.

Figure 5.3 displays the responses of the children to Question 2 in Table 5.2. The aim of designing this question is to see what kind of game children love and guide future development of computer games dedicated to pediatric rehabilitation. Brown and dark blue were used to indicate children at 5 to 6 years old and children at 7 to 10 years old respectively. From the figure, it can be seen that 6 of the 7 children like the "Rabbit and fish game" best among the 3 implemented computer games and one older child, whose functional ability was the best among the seven children according to therapists involved, choose "Gate game" as her favourite game. From the explanations given by the children, the 6 children chose "Rabbit and fish game" because this game is the easiest as well as the most interesting one among the 3 games. This indicates that computer games dedicated to pediatric rehabilitation should not be too challenging, so that children can have some "sense of achievement" after playing with the game.

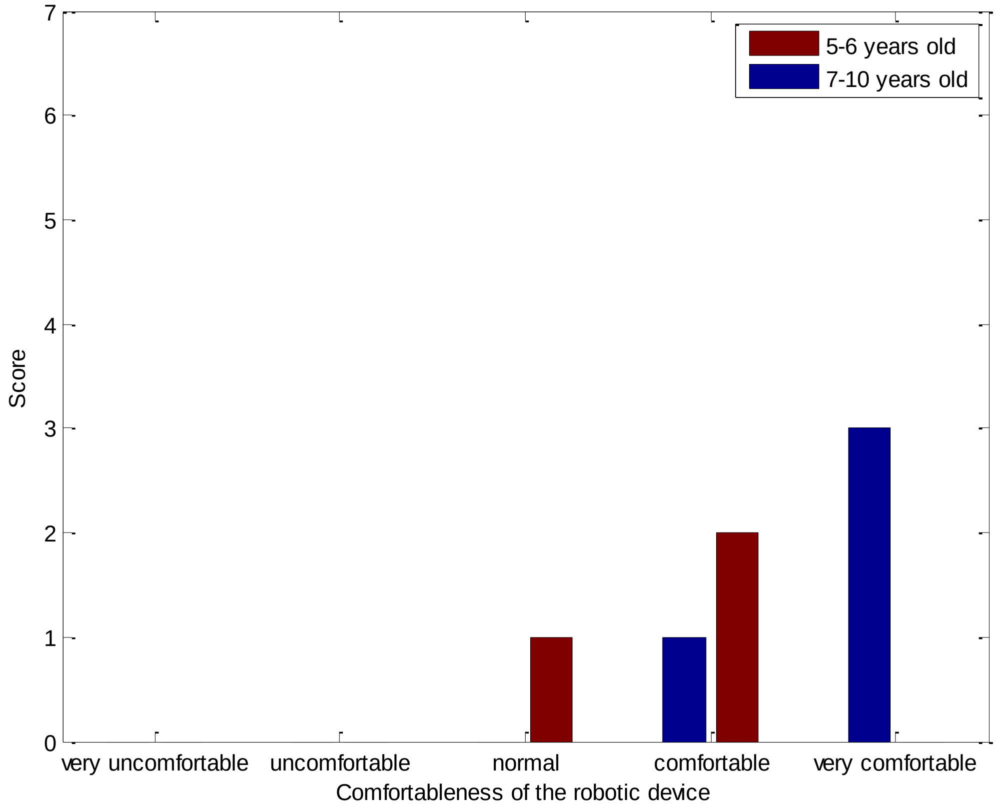


Figure 5.4: The statistical result of Question 3 in Table 5.2.

Figure 5.4 shows the responses of the children to Question 3 in Table 5.2. The objective of this question is to see whether the children can comfortably use the robotic device and if any modifications are required. Brown and dark blue were used to indicate children at 5 to 6 years old and children at 7 to 10 years old respectively. From the figure, it can be seen that older children generally felt more comfortable to use the robotic device compared to younger children. This may be because younger children generally have weak functional ability in using their upper limbs, which may make it more challenging for them to complete the required tasks.

Figure 5.5 illustrates the responses of the children to Question 4 in Table

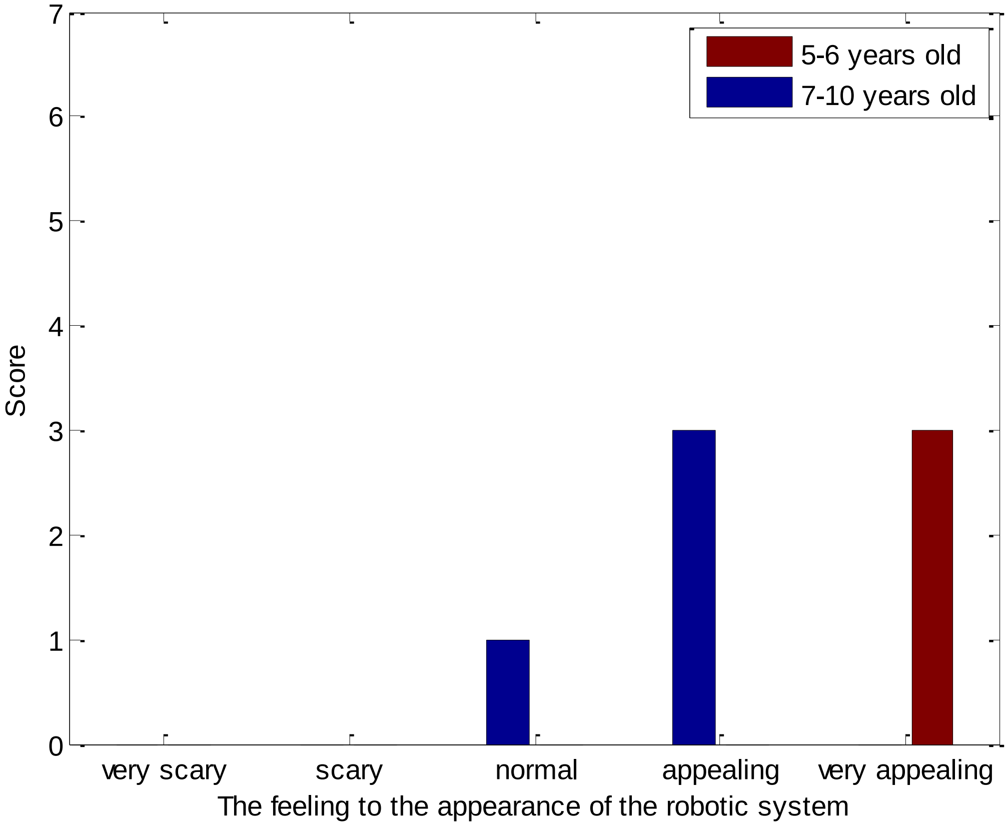


Figure 5.5: The statistical result of Question 4 in Table 5.2.

5.2. The goal of this question is to see whether the children are afraid of using the robotic device since fear of technology is often observed in adult rehabilitation (Lambercy [2009]). Brown and dark blue were used to indicate children at 5 to 6 years old and children at 7 to 10 years old respectively. From the figure, we can see all the children are not afraid to use the robot. In fact, they like this new technology, which is different from the observation in adult rehabilitation. This may indicate robot-assisted rehabilitation may suit better to the needs of children compared to adults.

Compared to the questionnaire on the children, only one question was prepared to the parents. The aim of designing this question is to obtain the parents' opinions on whether the developed computer games can engage their children. Fig. 5.6 shows the result to Question 1 in Table 5.3. Brown and dark blue were used to indicate the parent's child is at 5 to 6 years old and children at 7 to 10 years old respectively. A general observation

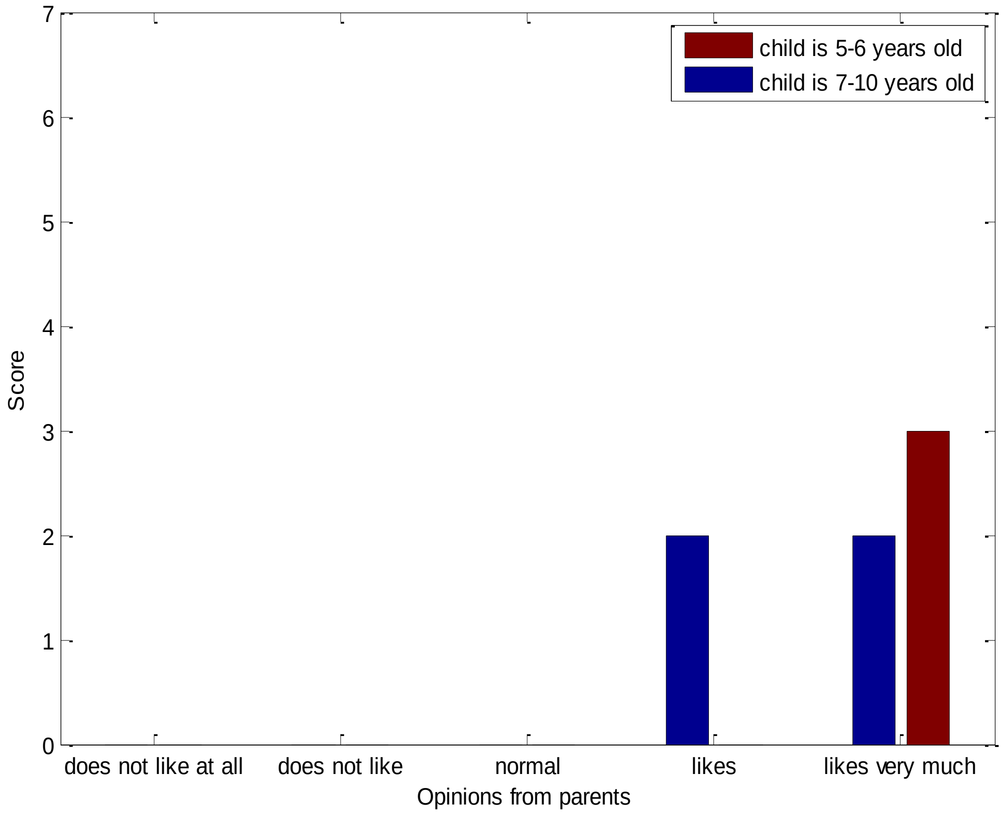


Figure 5.6: The statistical result of Question 1 in Table 5.3.

would be all the parents believe their children like the robotic system. In particular, the figure shows similar results obtained from the questionnaire to children, i.e. younger children seem like the computer games more compared to older ones, as shown in fig. 5.2, which enhances the reliability of the results from the questionnaires.

5.3.2 Results from behavior analysis

To increase the reliability of the results from the questionnaires, behavior analysis was used. The 60-minute robotic test of the seven children were recorded by a camera. After all the sessions, we replayed the videos and analysed the children's behaviors. According to the degree of participation, the behaviors can be classified into two main categories: high-interactive and low-interactive (Haibin [2012]). High-interactive behaviors generally consist of gaze, smile and speech while interacting with robotic devices. Low-interactive behaviors include looking at other stuff without focusing on the screen or operating with depressed expression.

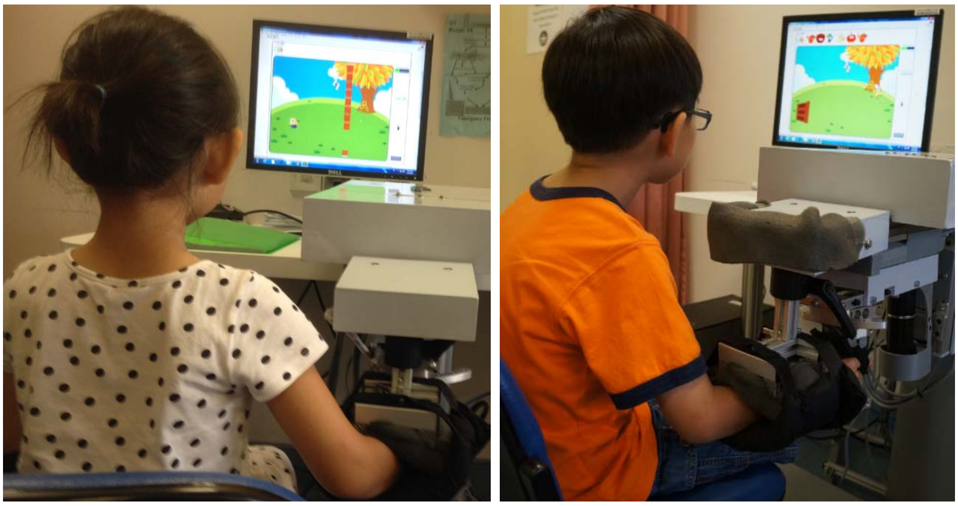


Figure 5.7: Two examples of the children's gaze behavior.

Gaze behavior: For children, gaze behavior was often observed when they see something they are interested in. During the 60-minute robotic tests, gaze behavior is the most frequently observed behavior. Children generally kept focusing their attention on the screen while they were playing the games since they would have a high chance to fail if they chose not to.

After finishing one set of trials, which only takes several minutes or even shorter time, children would have a short period of time to choose their reward cartoon characters and also relax. This could prevent any fatigue encountered for their eyes. Fig. 5.7 displays two examples of the children's gaze behavior during the interaction.

Smile behavior: Smile behavior, an expression human used as a sign of joy and happiness, was another very often observed behavior during the 60-minute tests. This kind of behavior may occur after the children saw new cartoon characters, after they completed one trial and succeeded or after they completed one set of trials and received positive feedback ("super job" or "well done") from the game interface. Interestingly, we found that

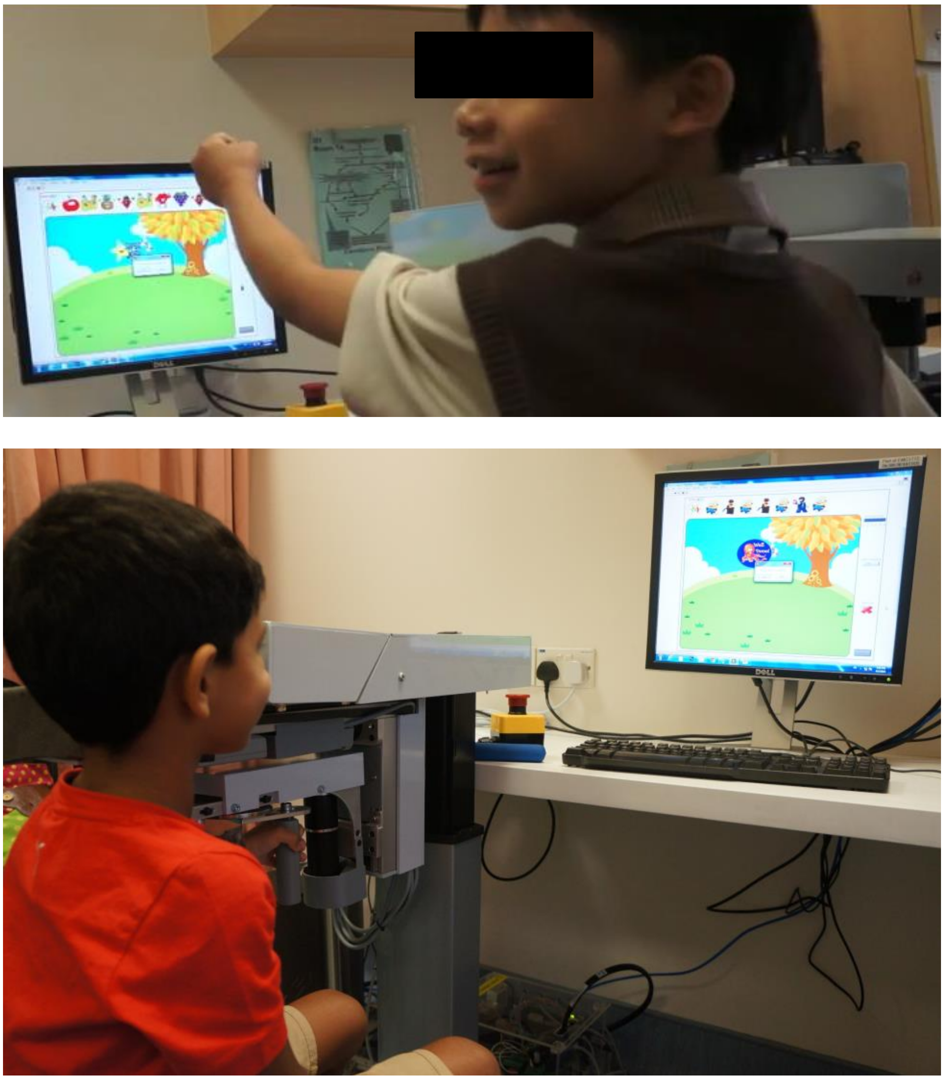


Figure 5.8: Two examples of the children's smile behavior.

younger children (5 to 6 years old) seemed to smile more than older ones (7 to 10 years old), which significantly correlates with their responses of the feeling to the games as shown in Figure 5.2.

In addition, younger children had other body languages such as giving a high five to his/her parent and raising his/her unaffected hand to cheer up for his/her performance, which generally occurred after they finished one set of trials and achieved good results. Fig. 5.8 shows two examples of the children's smile behavior.

Speech behavior: Compared to smile and gaze behaviors, speech behavior was less often observed in the interaction. Generally, speech behavior occurred in the situation that children saw their favourite cartoon characters or the one they liked a lot. For example, subject 1 said: “Look! this is a fish banana”, after he saw a cute banana character which looks like a fish. Subject 2 said: Wow, I saved the ‘Batman’, after he managed to guide the ‘Batman cartoon’ to pass the hole in the gate. In particular, we found younger children talked more during the interaction. The reason could be that they had stronger feelings to the games as indicated by results from the questionnaires.

In addition to gaze, smile and speech behaviors, some low-interactive behaviors were also observed during the interaction. For example, subject 6’s supination function was relatively weak. After he finished around 15 minutes pinching exercise and rest, he started the forearm supination/pronation exercise. The subject said: “I want to play the first one and this is difficult” after several minutes’ playing and the game arrived at a more difficult level. Sometimes he didn’t look at the screen and kept looking at his affected hand, which was interacting with the robotic device. The reason should be the kid felt discouraged after he failed in several trials at higher difficult levels. This indicates that sometimes we need to manually decrease the difficulty level of the game to fit the children’s moods, thus leading to active participation and engagement of the children.

Furthermore, subject 6 asked for a break, which was also the only break requested by the 7 children, while he was practicing the forearm supination/pronation movement and felt discouraged after he failed in several trials. After we manually adjusted the difficulty level of the game to a lower level, he restarted the test.

5.3.3 Discussion

To evaluate our robotic device together with the implemented interactive computer games and see whether children can be engaged throughout a 60-minute robotic test, we used questionnaires and behavior analysis methods. After analysing the results from the two methods, we found a good consistency between the two. Generally, all children like the developed games and can be engaged throughout the 60-minute robotic interaction.

More specifically, we found younger children (5-6 years old) liked the implemented games more compared to older ones (7-10 years old) and they all preferred the game (*Rabbit and fish games*), which was also easy for them. In addition, older children seemed to be able to interact with the robot more comfortably than younger children, who felt normal or comfortable while using the robotic device.

Interestingly, we didn't find any child that was afraid to use the robotic device, which is different from adult rehabilitation where fear of technology is very often observed. This indicates that robot-assisted rehabilitation therapy may serve the needs of children better since they generally like computer games and new technology.

5.4 Summary

Compared to adult rehabilitation systems, special attention should be given to active participation and engagement in children rehabilitation since children generally only focus on stuff they are interested in and they may refuse to use the robotic system if they feel bored. In order to evaluate whether the developed robotic device together with the implemented computer games can engage children throughout a 60-minute test and whether the children can comfortably use the device, we have conducted a pilot study as described in this chapter. Seven CP children aged from 5-10 years old joined in the study. Two types of methods (questionnaires and behavior analysis) were used to annotate the children's feelings to the robotic system. Results from the two methods suggest that all children can comfortably interact with the robotic system and younger children liked the implemented games more compared to older ones. Yet, older children felt more comfortable while using the robotic device. However, one younger child appeared discouraged after failing several times in one set of trials and we needed to manually decrease the difficulty level of the game to keep engaging the subject.

Results from the study showed that our developed games are interesting to children and may be suitable to be used for the clinical trials. Unlike adults, who may be very cooperative and actively participate while training even they feel bored, children would refuse or act very uncooperative if they feel bored. Therefore, special attention should be given to the design of interactive computer games for pediatric rehabilitation.

Chapter 6

Clinical study

6.1 Introduction

Following the positive results from the pilot study, a clinical study has been conducted at NUH, Singapore. The clinical study described in this chapter is still ongoing with planned 20 CP children to investigate the feasibility of using the reachMAN2 as a rehabilitation tool, analyze the reactions of CP children after training with the robotic device, and quantify potential benefits of therapy with the reachMAN2. The protocol and the results of the clinical study with 5 CP children who had completed their robotic rehabilitation therapies by the time of writing this thesis are presented in the chapter.

6.2 Methods

6.2.1 Subjects

The research study was approved by the institutional ethics committee of NUH, Singapore and informed consent was obtained prior to participation.

Five CP children participated in the robot-assisted rehabilitation study. They were all able to understand the instructions on how to use the robotic device and had no visual or hearing impairments. Table 6.1 summarizes some of the information on the 5 CP children who participated in the pilot study.

Table 6.1: Information on the 5 CP children involved in the clinical study.

subject	*gender*	*age (year:mon)*	*affected hand*	*dominant hand*	*Cognition*
S1	M	8:5	right	left	Normal
S2	M	5:7	left	right	Normal
S3	M	7:8	right	left	Normal
S4	F	12:7	left	right	Normal
S5	M	7:6	left	right	Normal

6.2.2 Protocol

The subjects sat in an upright position with the forearm placed on the padded arm support and the hand holding the handle of the reachMAN2. The height of the device could be adjusted to offer the subject a comfortable position (Fig. 6.1). Velcro bands were used to strap the subject's hand on to the device.

The subjects underwent robot-assisted physical therapy for 10 sessions over 4 weeks and functional assessments three times with a therapist. The experimental protocol of the clinical study is shown in Fig. 6.2 and the detailed arrangement of the 13 visits about the experiment is as follows:

- Visit 1 (Week 1):

  A comprehensive assessment (Pre-assessment) was conducted by the pediatric occupational therapist involved in this study to test the subjects' abilities prior to the robot-assisted physical therapy. This includes:

Figure 6.1: A subject (male, 7 years old) training with the reachMAN2.

- Body Function Level
  - measurement of range of motion using a goniometer.

    a) forearm supination/pronation

    b) wrist extension/flexion
  - measurement of hand grip strength using a handheld dynamometer
  - measurement of key pinch strength (thumb and finger function) using a handheld dynamometer
- Activity Level

  Activity Level was assessed through the Bruininks-Oseretsky Test of Motor Proficiency, Second Edition (BOT-2) (Deitz et al. [2007]) using the subtests of fine motor precision, fine motor integration and manual dexterity. The BOT-2 is a norm referenced standardised motor assessment available in a Complete Form with 53 items or a Short Form with 14 items selected from the Complete Form (Lucas et al. [2013]).

- Visit 2-11 (Week 2-5):

  The subjects underwent robotic assisted physical therapy, with two or three sessions per week and 10 sessions in four weeks, under the guidance and monitoring by a research assistant to ensure that he/she continues to be engaged with the task safely.

  Each session lasted around 1 hour and the subjects started with the pinching exercise followed by forearm supination/pronation exercise, then by wrist flexion/extension exercise. The subjects were asked to perform each exercise for around 15 minutes and a two-minute rest time was given between each exercise. During the second and eleventh visits, the subjects underwent 5 sets (50 in total) of corresponding robotic assessment after each type of robotic therapy as shown in Fig. 6.2. The same game (gate game) with the same parameters such as level of difficulty and range of motion, which were decided according to the performances of the subjects during the first robotic therapy session, was used in the two assessments for the subject. The two sets of results were used to evaluate whether there is any improvement after the robotic therapy.

  The subjects can start with any of the 3 games discussed in chapter 4 according to their preferences and they all started from level 1 of the interactive games and then the computer games adapted to the performance of the subjects during therapy once they pass the requirements to increase difficulty level. Moreover, subjects did not receive any other form of rehabilitation intervention during the therapy.

- Visit 12 (week 6):

  Assessments (post-assessment) were performed as described in Visit 1. This set of results was used to compare to that prior to the use of the robotic assisted physical therapy.

- Visit 13 (week 14):

  At 3 months after completion of the robotic therapy, the same assessments (3 months post-assessment) were performed as described in Visit 1. This set of results was also used to compare to that prior to the use of the robotic assisted physical therapy to see if the beneficial effects, if any, were sustained.

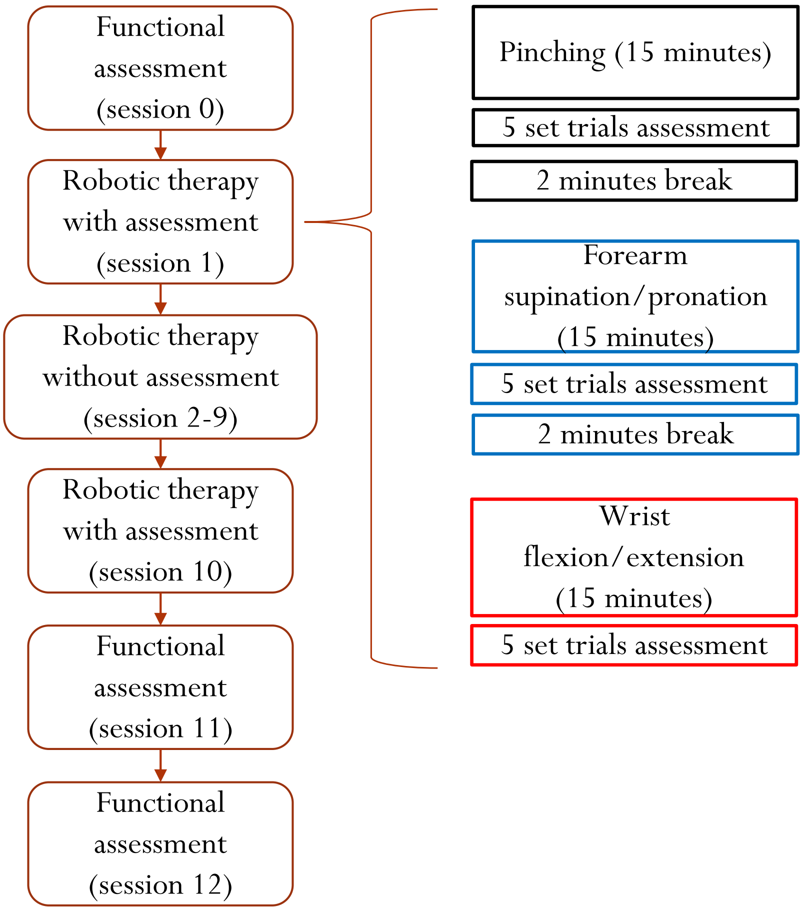


Figure 6.2: Experimental protocol of the clinical study with the reach-MAN2.

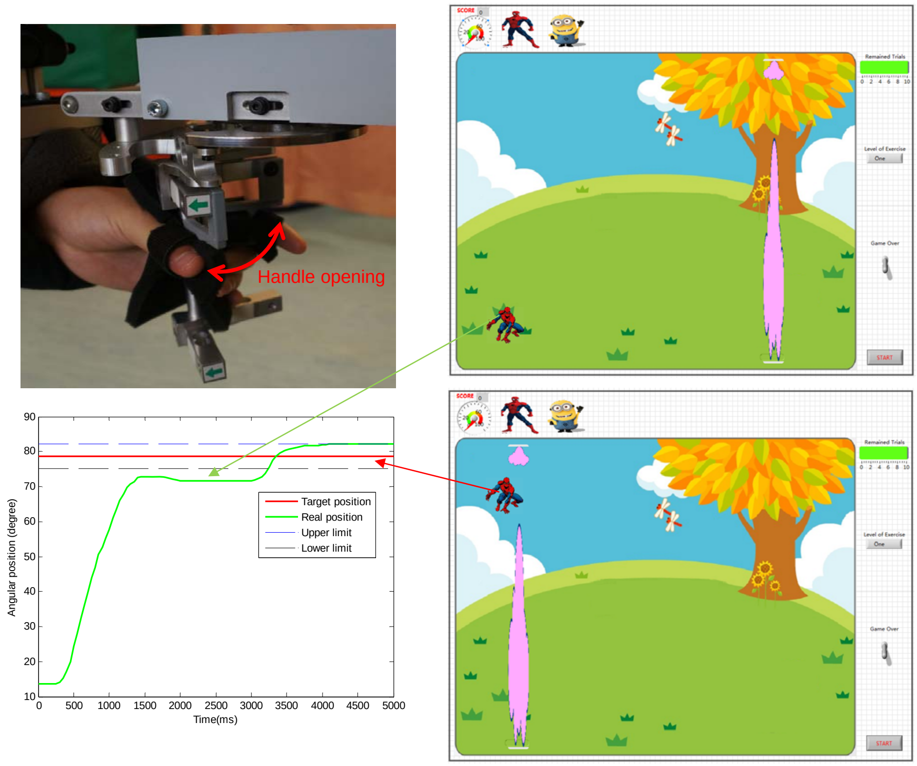


Figure 6.3: Hand position on the reachMAN2 during pinching exercise. Visual feedback was given by means of a cartoon character moving up and down as a function of the angular position of the handle.

6.2.3 Exercises

The subjects were asked to perform 3 exercises, i.e. pinching, forearm supination/pronation and wrist flexion/extension individually. The detailed information about the 3 exercises are as follows:

- In the pinching exercise, the subjects started with the closed hand position and had to open or close the handle with the thumb and index finger to play the games described in chapter 4. Both the opening and closing of the exercise are active, i.e. the subject initiates and controls the motion of the exercise.

  For the gate game used in the robot assessments, the reference time, i.e. the maximum time given to subjects to complete the task, and the resistance or assistive force/torque vary according to the difficulty levels of the game. The detailed information can be found in Table

6.2. Simple visual feedback was given by means of an attractive cartoon character progressively moving up and down on the monitor as the subject opening/closing the handle of the reachMAN2 (Fig. 6.3).

- In the forearm supination/pronation exercise, the subjects started with forearm rotation at neutral position (angle = 0°) and had to rotate the device counter-clockwise or clockwise direction to play the games described in chapter 4.

  For the gate game used in the robot assessments, the reference time, i.e. the maximum time given to subjects to complete the task, and the resistance or assistive force/torque vary according to the difficulty levels of the game (Table 6.2). Simple visual feedback was given by means of an attractive cartoon character progressively moving left and right on the monitor as the subject rotating the handle of the reachMAN2 (Fig. 6.4).

- In the wrist flexion/extension exercise, the subjects started with normal wrist position and rotated the device clockwise or counter-clockwise direction to interact with the games described in chapter 4.

  For the gate game used in the robot assessments, the reference time, i.e. the maximum time given to subjects to complete the task, and the resistance or assistive force/torque vary according to the difficulty levels of the game (Table 6.2). Simple visual feedback was given by means of an attractive cartoon character progressively moving left and right on the monitor as the subject rotating the handle of the reachMAN2 (Fig. 6.5).

The level of difficulty, i.e. the level of resistive or assistive force/torque, precision and the required time (reference time) to complete the specific

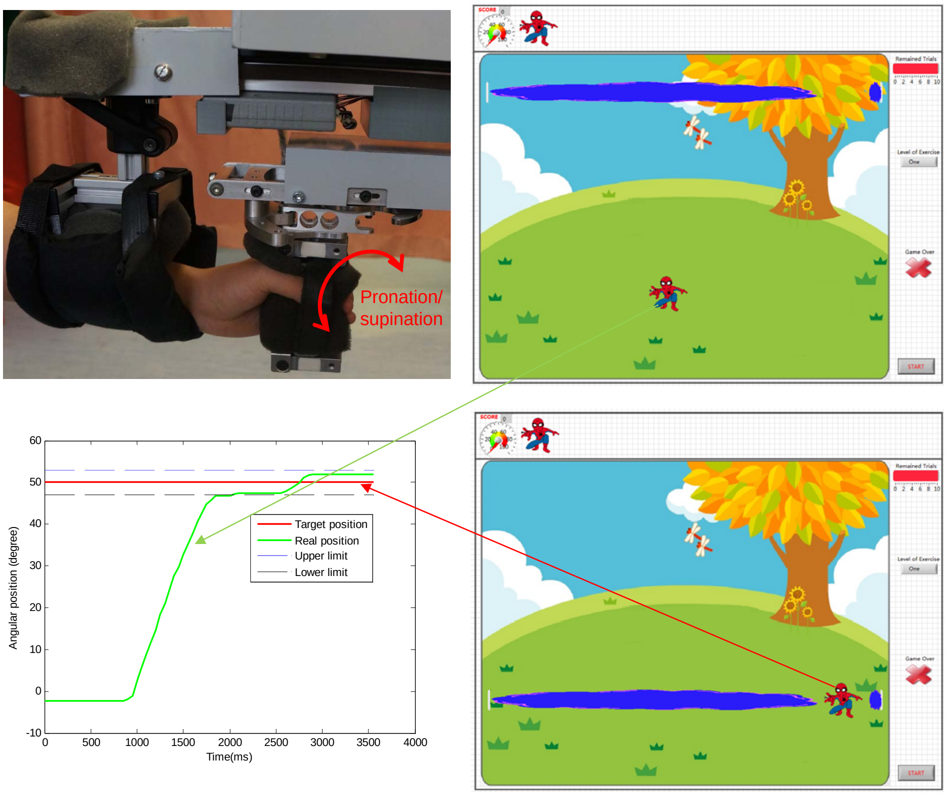


Figure 6.4: Hand position on the reachMAN2 during pronation/supination exercise. Visual feedback was given by means of a cartoon character moving left and right as a function of the angular position of the handle.

task were adapted automatically to the performance of the subject during the robotic therapy. Table 6.2 shows the parameter settings for every level of the gate game, which were used for the robot assessments. Note that ROM and precision could be adjusted manually to adapt to the subjects' functional abilities in the two assessments.

6.2.4 Data analysis

The following parameters were used to quantify the effects of the robotic assisted physical therapy:

- the number of cartoon characters that successfully passed through the gate in one set of trials for all the three exercises, S_p (*success score*).

Table 6.2: Parameters on all difficulty levels for all exercises in the clinical study

Pinching exercise

Level	*ROM (°)*	*Precision (°)*	*Reference time (s)*	*Force (N)*
1	68	4.4	5.1	0.5
2	70	4.3	4.7	1
3	73	4.2	4.3	2
4	76	4.0	4.0	4
5	79	3.6	3.5	5
6	82	3.3	3.1	6
7	85	3.3	2.9	7
8	89	3.3	2.8	8
9	90	3.0	2.7	9
10	90	2.6	2.5	10

Supination/pronation exercise

Level	*ROM (°)*	*Precision (°)*	*Reference time (s)*	*Torque (Nm)*
1	38	4.3	6.1	0.01
2	39	4.2	4.3	0.02
3	41	4.1	3.3	0.04
4	42	3.7	2.7	0.08
5	44	3.2	2.7	0.15
6	46	2.9	2.7	0.30
7	47	2.9	2.7	0.40
8	49	3.3	2.7	0.50
9	50	3.0	2.2	0.60
10	50	2.6	2.0	0.80

Flexion/extension exercise

Level	*ROM (°)*	*Precision (°)*	*Reference time (s)*	*Torque (Nm)*
1	34	3.9	6.1	0.1
2	35	3.8	5.4	0.15
3	37	3.7	4.3	0.2
4	38	3.3	3.6	0.25
5	39	2.9	2.9	0.3
6	41	2.6	2.7	0.35
7	43	2.6	2.5	0.4
8	44	2.6	2.4	0.45
9	45	2.6	2.2	0.5
10	45	2.1	2.0	0.6

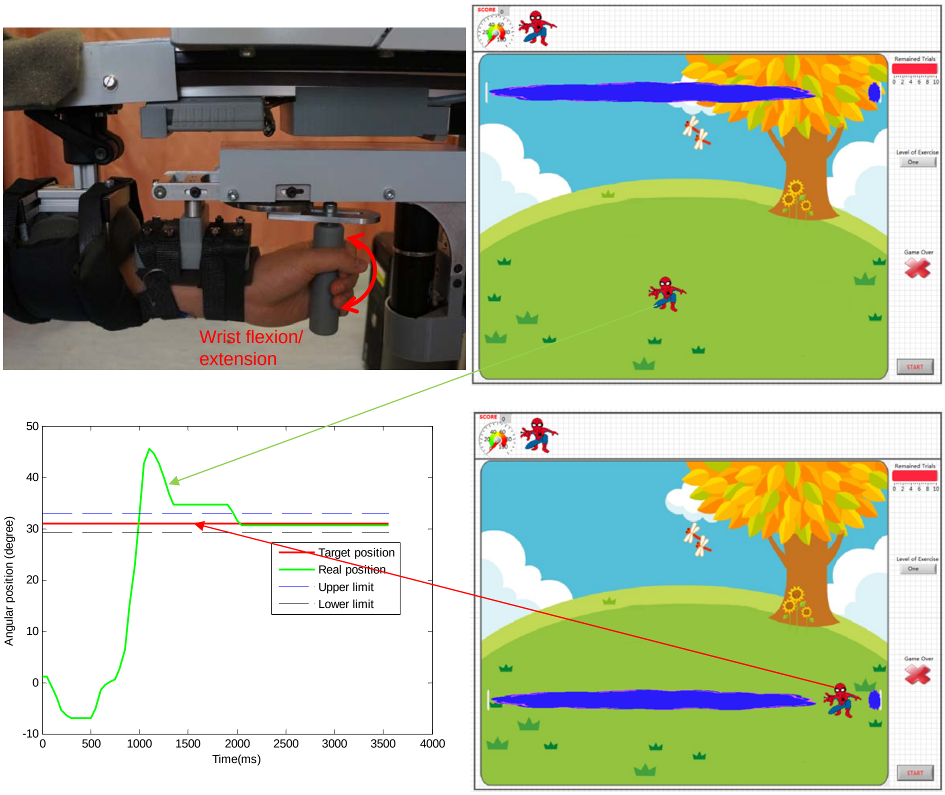


Figure 6.5: Hand position on the reachMAN2 during wrist flexion/extension exercise. Visual feedback was given by means of a cartoon character moving left and right as a function of the angular position of the handle.

- the precision score (Equ. 4.2) of all 10 trials in one set described in chapter 4, S (*precision score*).
- movement mean speed was evaluated by the *mean speed* (M_s) of all 10 trials in one set, which would be used to see whether subjects can perform faster movements after the robot-assisted therapy with the same given condition.
- motion smoothness was evaluated using velocity peaks metric. The velocity peaks metric is the number of *velocity peaks* in a speed profile. Less velocity peaks suggest better motion smoothness.

A paired sample t-test was used to determine if there is a significant difference between the mean values of the same measurements made under two different conditions, i.e. before and after the robotic assisted physical

Table 6.3: Parameters used in the assessments on each exercise for the five subjects

Exercise	*Parameter*	*S1*	*S2*	*S3*	*S4*	*S5*
Pinching	Level of exercise	5	1	2	3	1
	Range of motion (°)	67	72	75	73	68
Forearm supination/pronation	Level of exercise	7	2	3	5	1
	Range of motion (°)	46	41	43	44	38
Wrist flexion/extension	Level of exercise	8	6	6	4	6
	Range of motion (°)	31	44	44	38	41

therapy. Results were considered statistically significant if $p<0.05$.

The results of the functional assessments before and after the robotic assisted physical therapy are also presented. When compared to the pre-assessment results, significant improvement is achieved if there is an increase of $\geq 15\%$ in the:

- range of motion (angle measured in degrees)
- muscle strength (measured using a handheld dynamometer)

The minimum cut-off value of 15% improvement is decided based on comparison with other studies of hand function assessment in children with CP (Barroso et al. [2011]).

6.3 Results

6.3.1 Robot assessments

This section presents the patients' performance results assessed after session 1 (Pre-assessment) and session 10 (Post-assessment) of the robotic assisted physical therapy. The information on the parameters used in the assessments on each exercise for the five subjects is shown in Table 6.3.

Fig. 6.6-6.10 show the typical results of the five subjects' pinching performances in the pre and post-assessments. The red, black and blue dotted lines denote target position, lower and upper limits of the pinching movements, respectively. For the two assessments used in subject 1, there are 3 target positions (67°, 37.5° and 10°) and the movements can be from any of the positions to another (0° denotes hand closed configuration). The exact movements in the pre and post-assessments may be different. However, the subject performed 5 sets of trials, i.e. 50 trials in total, leading to similar movements in the pre and post-assessments. For the two assessments used in subjects 2 to 5, there are only 2 target positions and the subjects need to perform 5 hand opening and 5 opposite closing movements for pinching exercise, leading to exactly same movements in the two assessments.

A direct observation is that subject 1 and 4 could complete the required pinching movements including the hand opening and closing movements before and after the robotic therapy. However, subjects 2, 3 and 5 were unable to complete the opening part of the pinching movements as required. After the robotic therapy, all subjects could complete the opening tasks very well and both the opening and closing movements seem more direct and smoother.

Fig. 6.11-6.15 present the typical results of the five subjects' forearm supination/pronation performances in the pre and post-assessments. Similar to the pinch exercise, for the two assessments used in subject 1, there are 3 target positions (-46°, 0° and 46°) and the movements can be from any one of the positions to another. The exact movements in the pre and post-assessments may be different. Nevertheless, the subject performed 5 sets of trials, i.e. 50 trials in total, leading to similar movements in the pre and post-assessments. For the two assessments used in subjects 2 to 5, there are three target positions (pronation target, neutral and supination target positions). In addition, the movements in the two assessments are exactly the same (5 supination and 5 pronation movements).

A direct observation is that subjects 1, 3, 4 and 5 were able to perform most of the required forearm supination and pronation tasks before and after the robotic therapy. However, before the robotic therapy, subject 2 could only perform some of the forearm pronation movements and was unable to perform forearm supination movements, especially those from 0° (neutral forearm position) to -46° (supination target position). After the robotic therapy, the subject was able to perform all the required tasks.

Fig. 6.16-6.20 show the typical results of the five subjects' wrist flexion/extension performances in the pre and post-assessments. For the two assessments used in subject 1, there are 3 target positions (-31°, 0° and 31°) and the movements can be from any one of the positions to another. The exact movements in the pre and post-assessments might be different. However, the subject performed 5 sets of trials, i.e. 50 trials in total, leading to similar movements in the pre and post-assessments. The two assessments used in subjects 2 to 5 have three target positions (flexion target, neutral and extension target positions). Furthermore, the movements in the two assessments are exactly the same (5 wrist flexion and 5 wrist extension movements).

A direct observation is that subjects 1, 3, 4 and 5 were capable of performing all the required wrist flexion/extension tasks before and after the robotic therapy. However, subject 2 was unable to perform the wrist extension movements from 0° (neutral position) to -44° (extension target position). After the robotic therapy, the subject was able to perform all the required tasks.

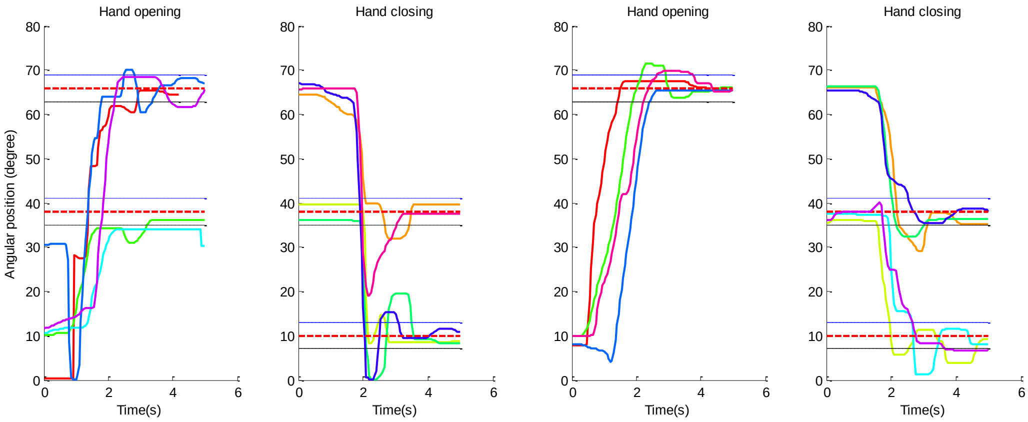


Figure 6.6: A typical result of subject 1's pinching performance in the pre (left) and post (right) assessments. Different colours stand for different trials and there are 10 trials in total for hand opening and closing movements. The red dotted lines are the target positions. The blue and black lines are the lower and upper limits around the target windows.

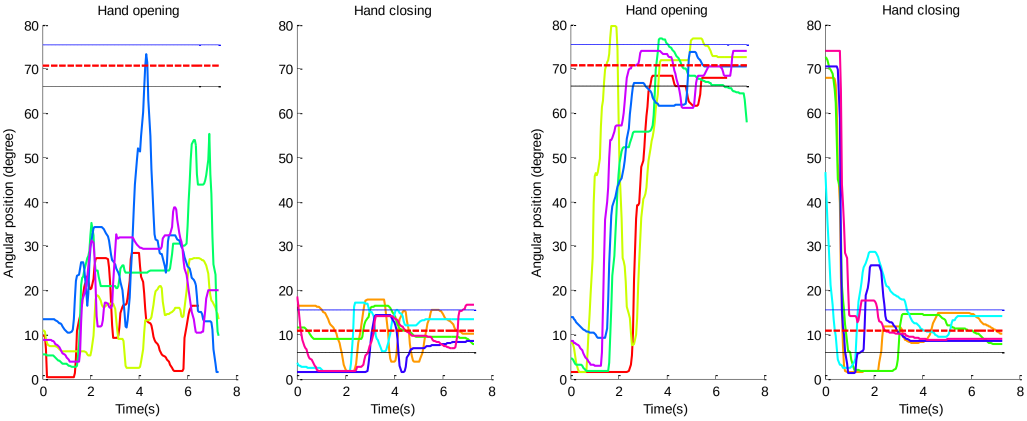


Figure 6.7: A typical result of subject 2's pinching performance in the pre (left) and post (right) assessments.

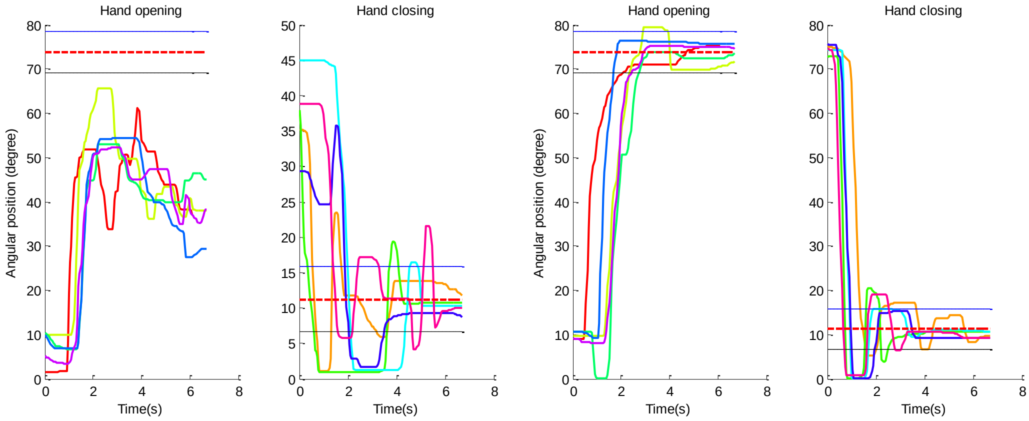


Figure 6.8: A typical result of subject 3's pinching performance in the pre (left) and post (right) assessments.

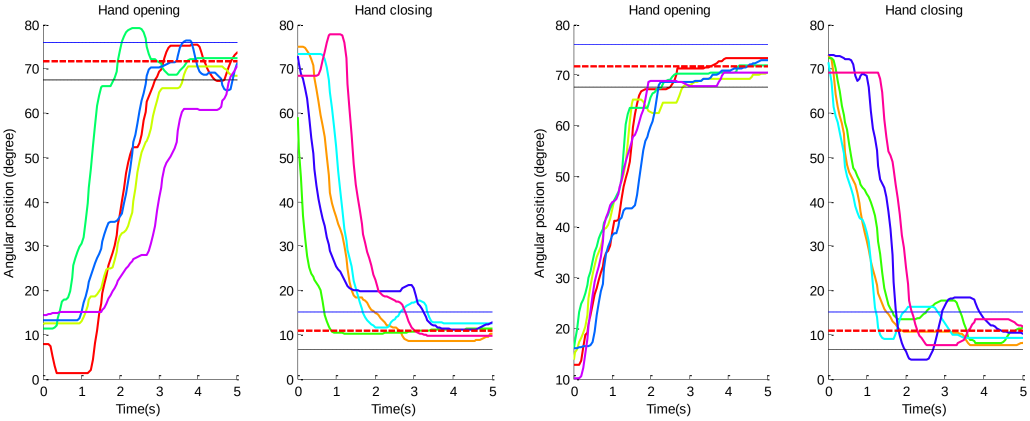


Figure 6.9: A typical result of subject 4's pinching performance in the pre (left) and post (right) assessments.

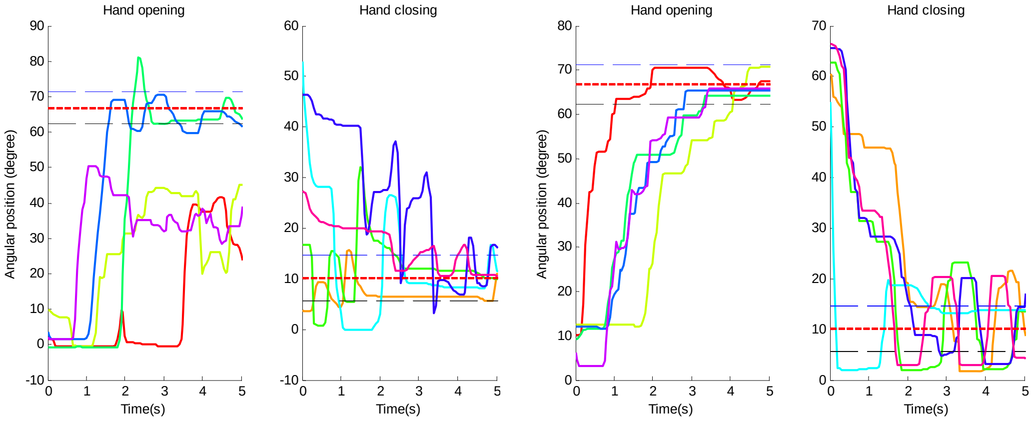


Figure 6.10: A typical result of subject 5's pinching performance in the pre (left) and post (right) assessments.

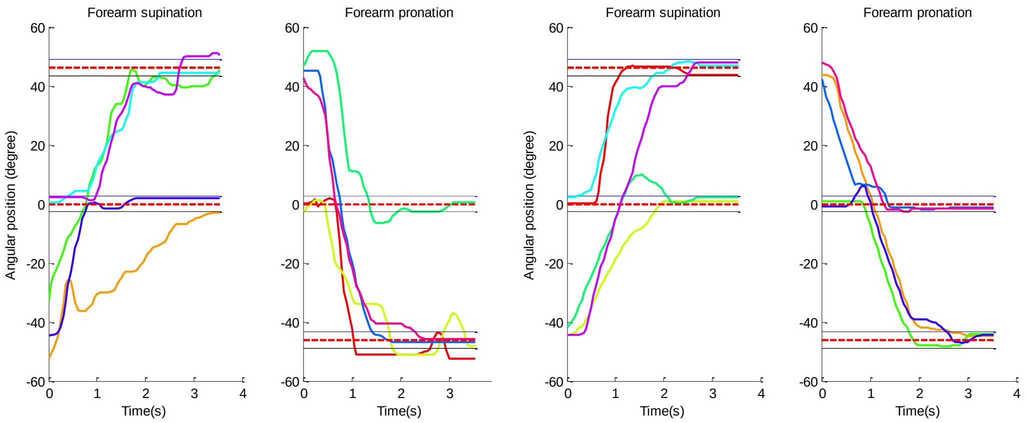


Figure 6.11: A typical result of subject 1's forearm supination/pronation performance in the pre (left) and post (right) assessments. Different colours stand for different trials and there are 10 trials in total for forearm supination and pronation movements. The red dotted lines are the target positions. The blue and black lines are the lower and upper limits around the target windows.

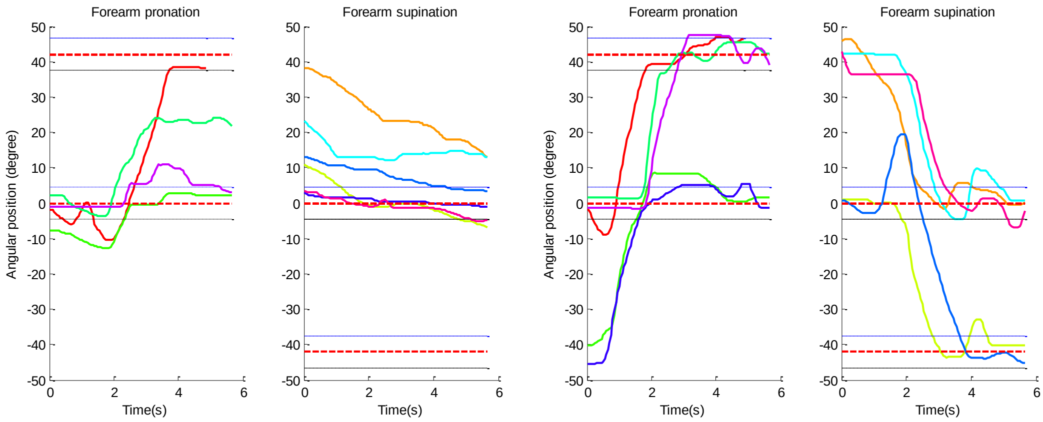


Figure 6.12: A typical result of subject 2's forearm supination/pronation performance in the pre (left) and post (right) assessments.

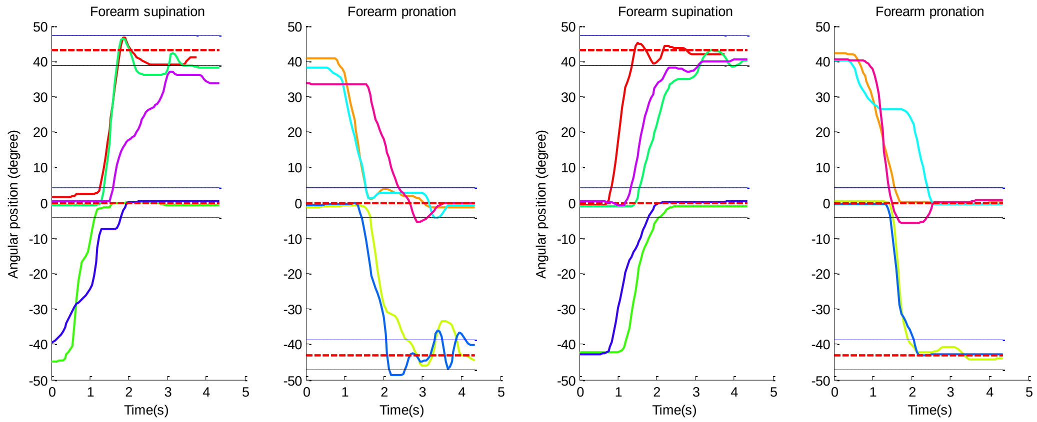


Figure 6.13: A typical result of subject 3's forearm supination/pronation performance in the pre (left) and post (right) assessments.

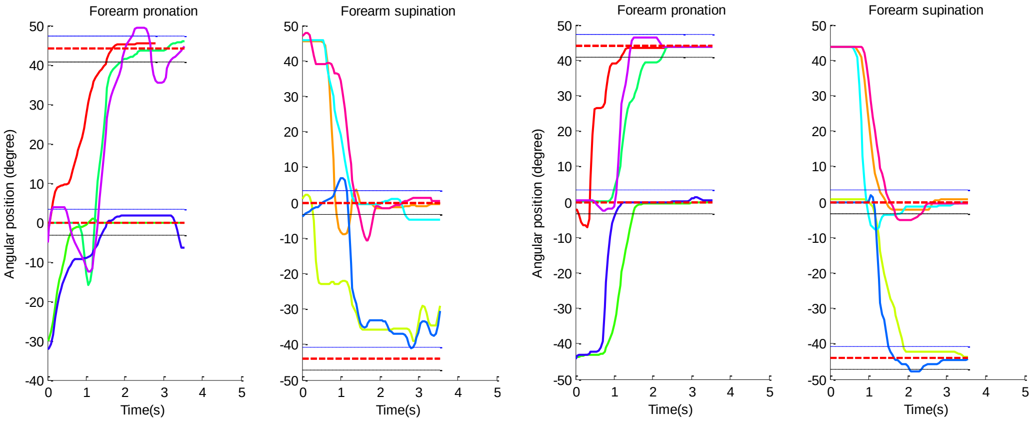


Figure 6.14: A typical result of subject 4's forearm supination/pronation performance in the pre (left) and post (right) assessments.

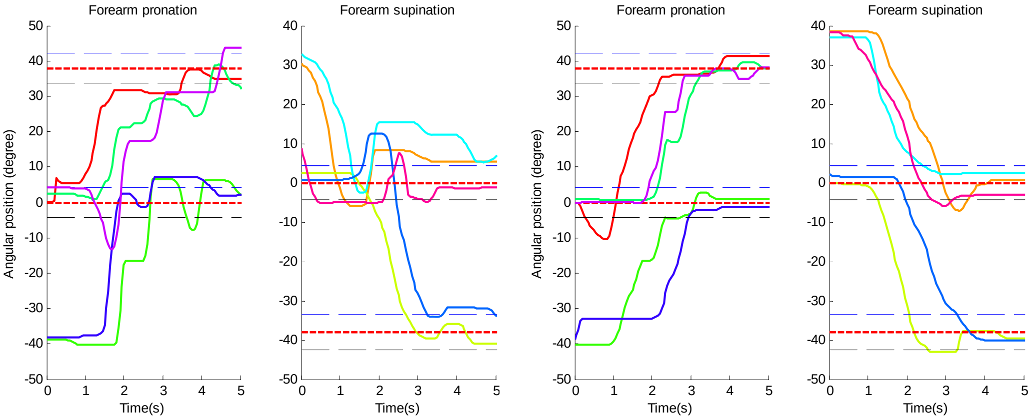


Figure 6.15: A typical result of subject 5's forearm supination/pronation performance in the pre (left) and post (right) assessments.

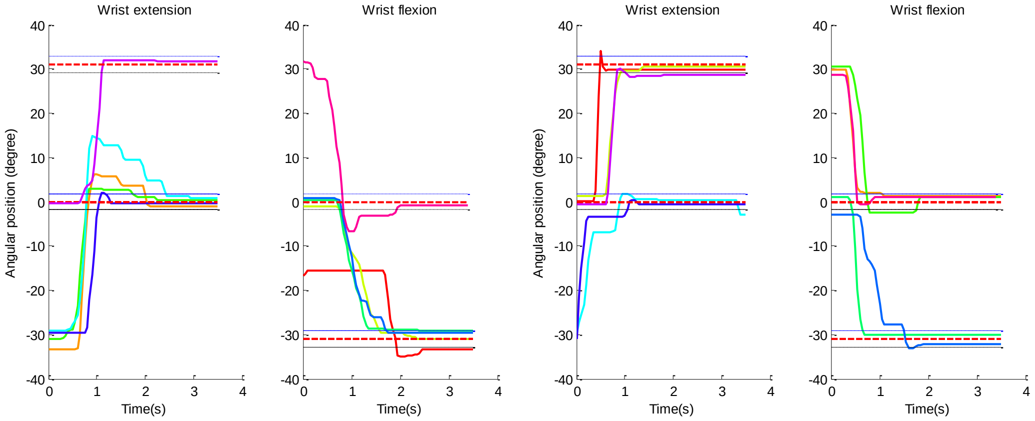


Figure 6.16: A typical result of subject 1's wrist flexion/extension performance in the pre (left) and post (right) assessments. Different colours stand for different trials and there are 10 trials in total for wrist flexion/extension movements. The red dotted lines are the target positions. The blue and black lines are the lower and upper limits around the target windows.

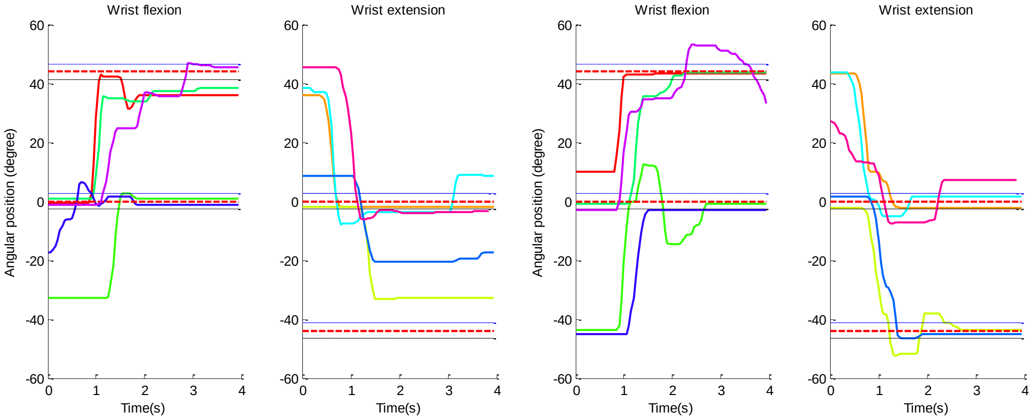


Figure 6.17: A typical result of subject 2's wrist flexion/extension performance in the pre (left) and post (right) assessments.

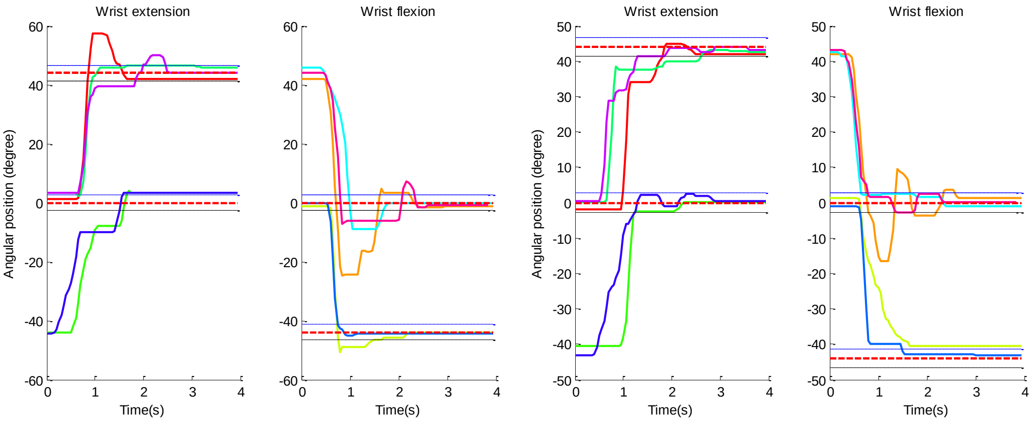


Figure 6.18: A typical result of subject 3's wrist flexion/extension performance in the pre (left) and post (right) assessments.

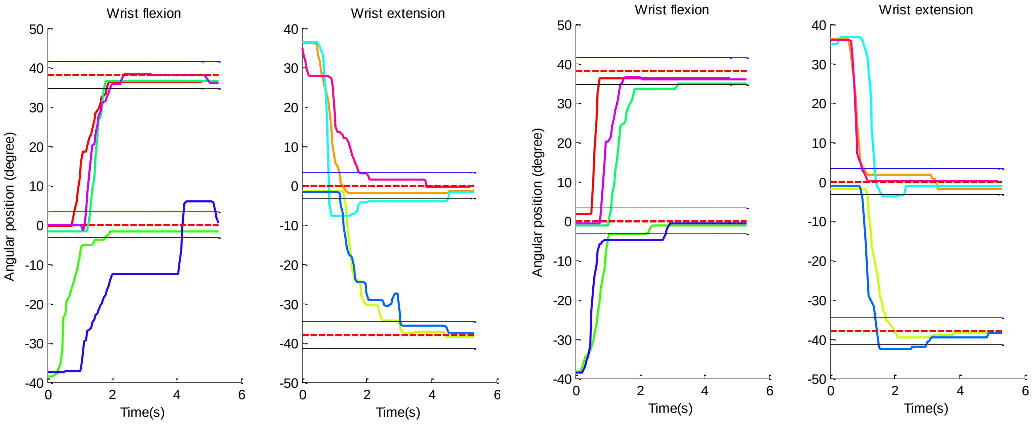


Figure 6.19: A typical result of subject 4's wrist flexion/extension performance in the pre (left) and post (right) assessments.

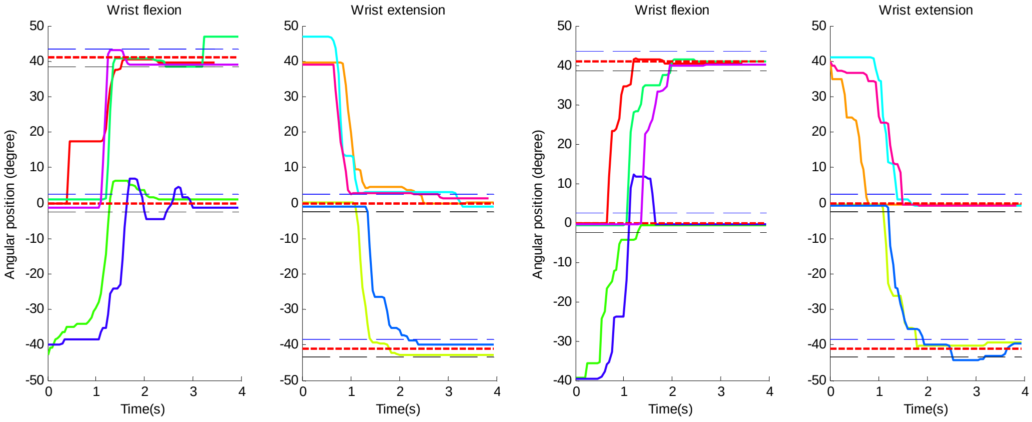


Figure 6.20: A typical result of subject 5's wrist flexion/extension performance in the pre (left) and post (right) assessments.

Fig. 6.21 and 6.22 show the *success scores* of the five subjects before and after the robot-assisted therapy for the three exercises. The diamond denotes the mean value and red line inside the box is the median value. The bottom and top of the box are the first and third quartiles, respectively. All subjects improved their scores for all the three exercises after the robotic therapy. Subject 1 started with very high scores in pinching and wrist flexion/extension exercises and a relative low score in forearm supination/pronation exercise. He improved the mean score by 6.8% ($p = 0.208$) from 8.8 to 9.4 for pinching movement, 71% ($p = 0.009$) from 4.2 to 7.6 for forearm supination/pronation movement and 22% ($p = 0.016$) from 7.2 to 8.8 for wrist flexion/extension movement. Subject 2 was weaker than subject 1 as indicated by the *success scores* and the levels of exercises used in the assessments. Subject 2 significantly improved the mean score by 153% ($p = 0.002$) from 3.4 to 8.6 for pinching exercise, 139% ($p = 0.001$) from 3.6 to 8.6 for forearm supination/pronation exercise and 44% ($p = 0.05$) from 5 to 7.2 for wrist flexion/extension exercise. Subject 3 significantly improved the mean score by 104% ($p < 0.001$) from 4.8 to 9.8 for pinching exercise, 37% ($p < 0.001$) from 7 to 9.6 for forearm supination/pronation exercise and 9.8% ($p = 0.1$) from 8.2 to 9 for wrist flexion/extension movement. Similarly, subject 4 improved the mean score by 31.6% ($p < 0.001$) from 7.6 to 10 for pinching exercise, 81% ($p = 0.005$) from 5.2 to 9.4 for forearm supination/pronation exercise and 16.3% ($p = 0.025$) from 8.6 to 10 for wrist flexion/extension movement. Subject 5 improved the mean score by 42% ($p = 0.019$) from 6.2 to 8.8 for pinching exercise, 39% ($p = 0.009$) from 7.2 to 10 for forearm supination/pronation exercise and 23% ($p = 0.035$) from 7 to 8.6 for wrist flexion/extension movement.

For the five subjects, all the scores improved, especially the scores for the pinching and forearm rotation exercises, and became very close to the maximum value 10 after the robot-assisted therapy, suggesting the subjects performed better and could complete most of the required tasks after the robotic therapy.

Fig. 6.23 and 6.24 display the *precision scores* of the five subjects before and after the robot-assisted therapy for the three exercises. All subjects improved their scores for all the three exercises after the robotic therapy. The scores in pinching and wrist flexion/extension exercises of subject 1 were relative high compared to the score in forearm supination/pronation exercise. Subject 1 improved the mean score by 34% ($p = 0.003$) from 39 to 52 for pinching exercise, 82% ($p = 0.007$) from 22 to 41 for forearm supination/pronation exercise and 20% ($p = 0.05$) from 42 to 50 for wrist flexion/extension exercise. Subject 2 was weaker than subject 1 as shown by the *precision scores* and the levels of exercises used in the assessments. In particular, subject 2 started from very low score values for pinching and forearm supination/pronation exercises. After the robotic therapy, subject 2 significantly improved his *precision score* by 139% ($p = 0.008$) from 21 to 52 for pinching exercise, 270% ($p < 0.001$) from 14 to 53 for forearm supination/pronation exercise and 36% ($p = 0.25$) from 31 to 42 for wrist flexion/extension exercise. Subject 3's pinching and forearm supination/pronation functions were weak before the robotic therapy and the *precision scores* were significantly improved by 147% ($p < 0.001$) from 30.2 to 74.6 for pinching exercise, 71% ($p = 0.017$) from 41.7 to 71.3 for forearm supination/pronation exercise and 17% ($p = 0.035$) from 48 to 55.9 for wrist flexion/extension exercise after the robotic therapy. Subject 4 improved the mean scores by 83% ($p = 0.005$) from 39 to 71.6 for pinching exercise, 93% ($p = 0.03$) from 30.8 to 59.5 for the forearm rotation exercise and 34% ($p = 0.05$) from 50.4 to 67.6 for wrist flexion/extension exercise. Subject 5 slightly improved the mean scores by 25.7% ($p = 0.068$) from 40.2 to 50.6 for pinching exercise, 70% ($p = 0.047$) from 45.4 to 77.1 for the forearm rotation exercise and 38% ($p = 0.072$) from 40.2 to 55.6 for the

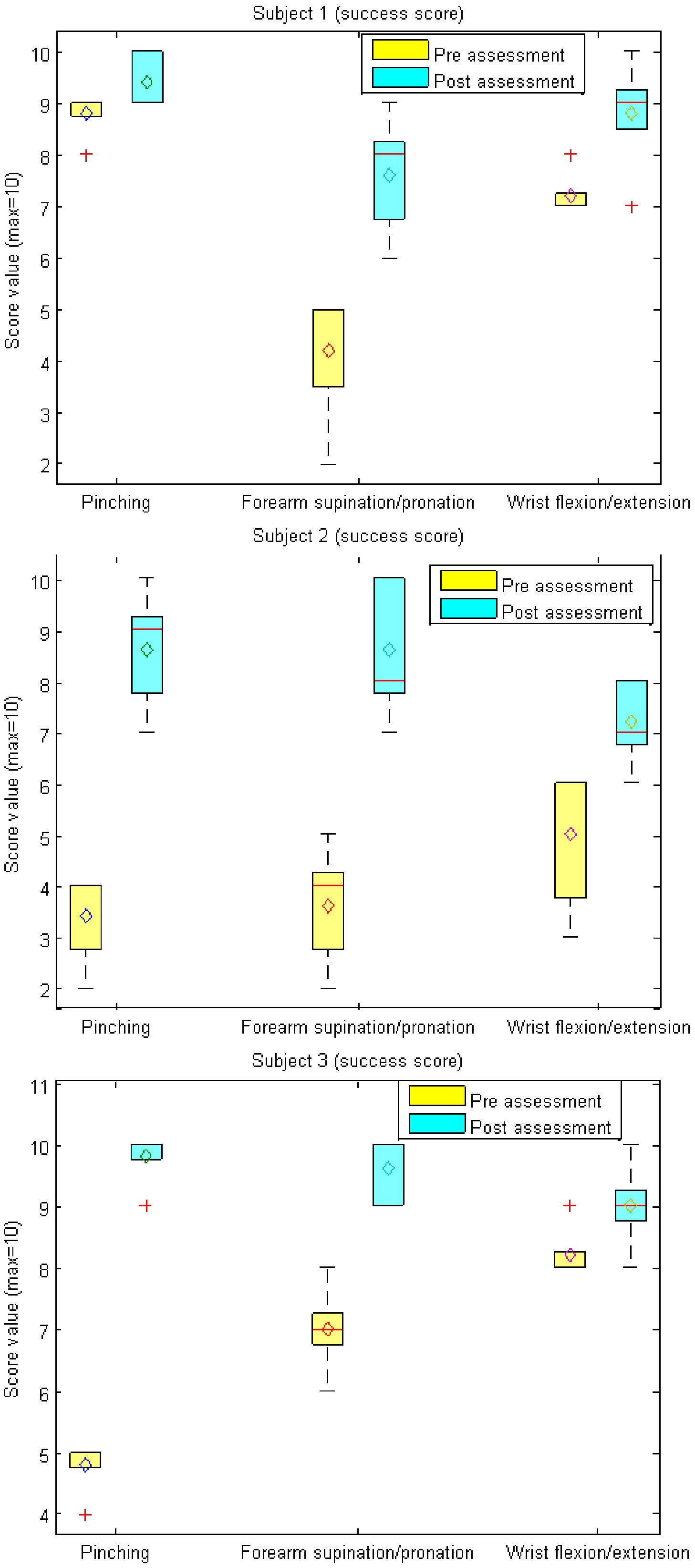


Figure 6.21: *Success scores* of the subjects 1, 2 and 3 before (pre) and after (post) the robotic therapy on the 3 exercises.

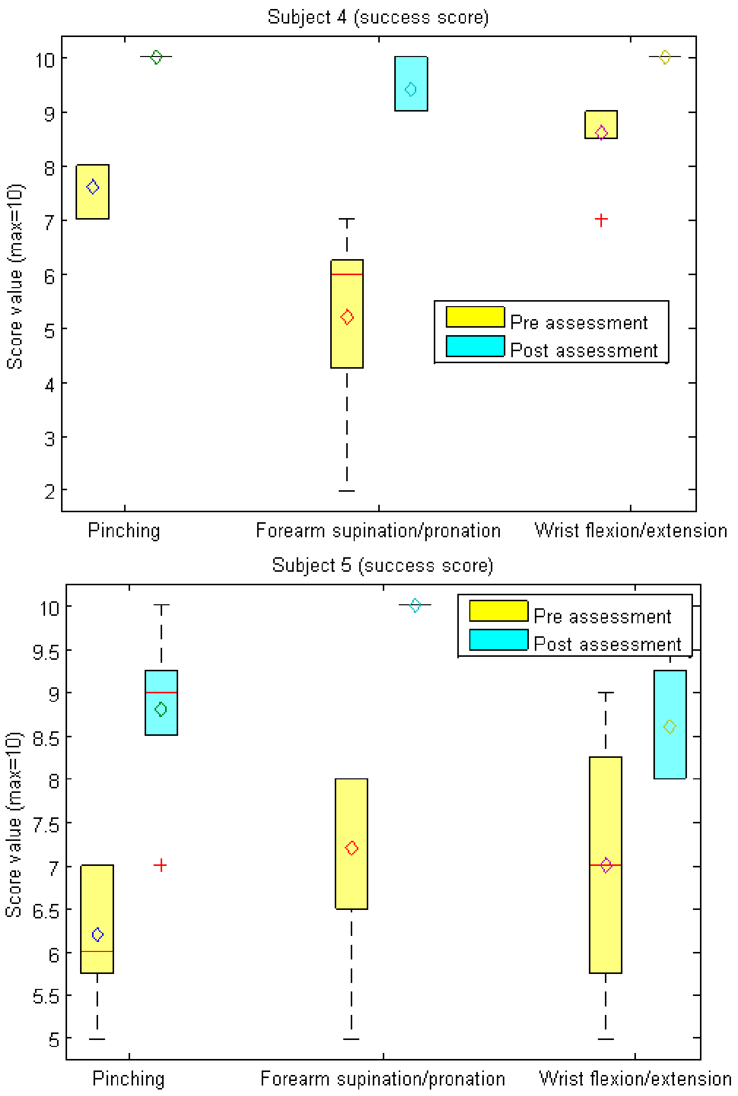


Figure 6.22: *Success scores* of the subjects 4 and 5 before (pre) and after (post) the robotic therapy on the 3 exercises.

wrist flexion/extension exercise.

For the three subjects, all the scores improved after the robotic therapy and significant improvements ($p < 0.05$) were observed in almost all the *precision scores* of pinching and forearm supination/pronation exercises for all subjects, suggesting all subjects could perform more precise movements after the robotic therapy.

Fig. 6.25 and 6.26 present the *mean speeds* of the five subjects before and after the robot-assisted therapy for the three exercises. Subject 1 improved the *mean speed* by 36.7% (p=0.029) from 27.4°/s to 37.4°/s for

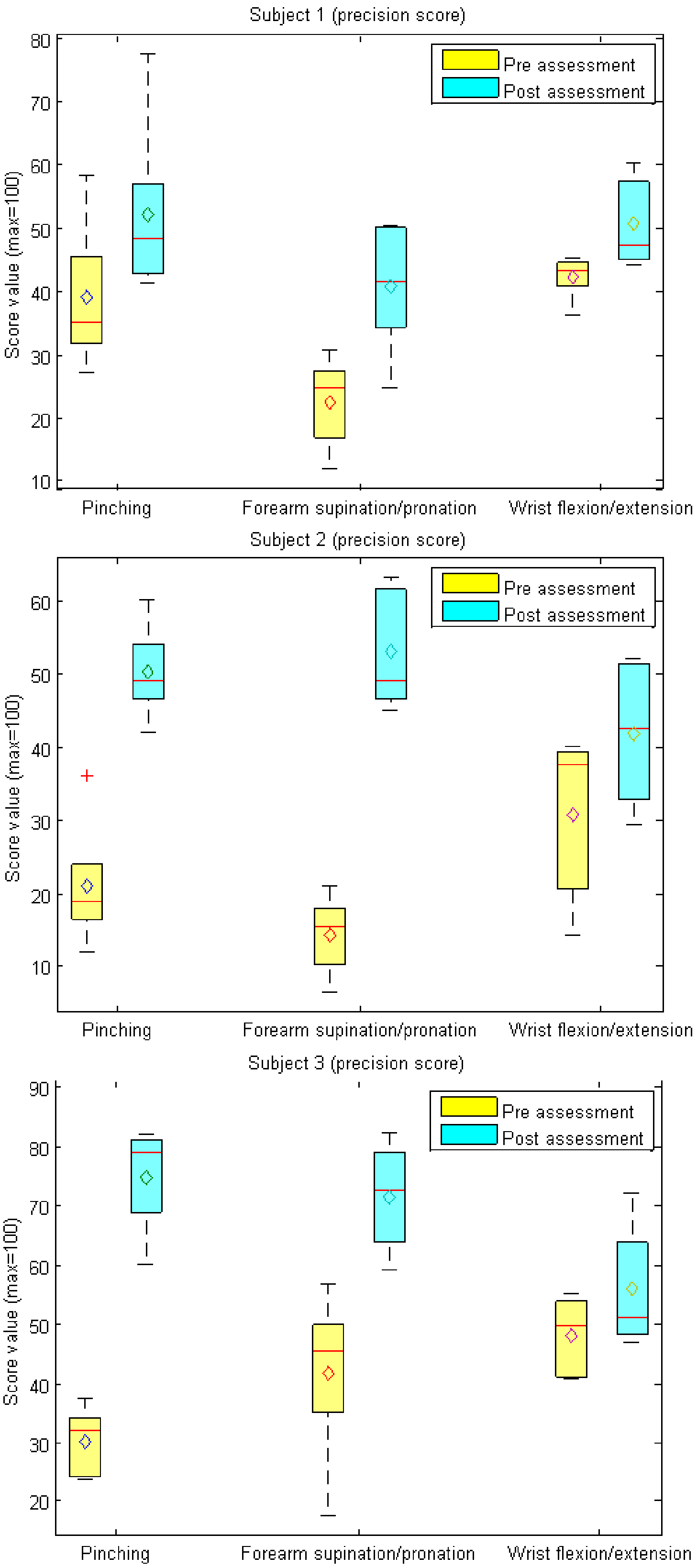


Figure 6.23: *Precision scores* of the subjects 1, 2 and 3 before (pre) and after (post) the robotic therapy on the 3 exercises.

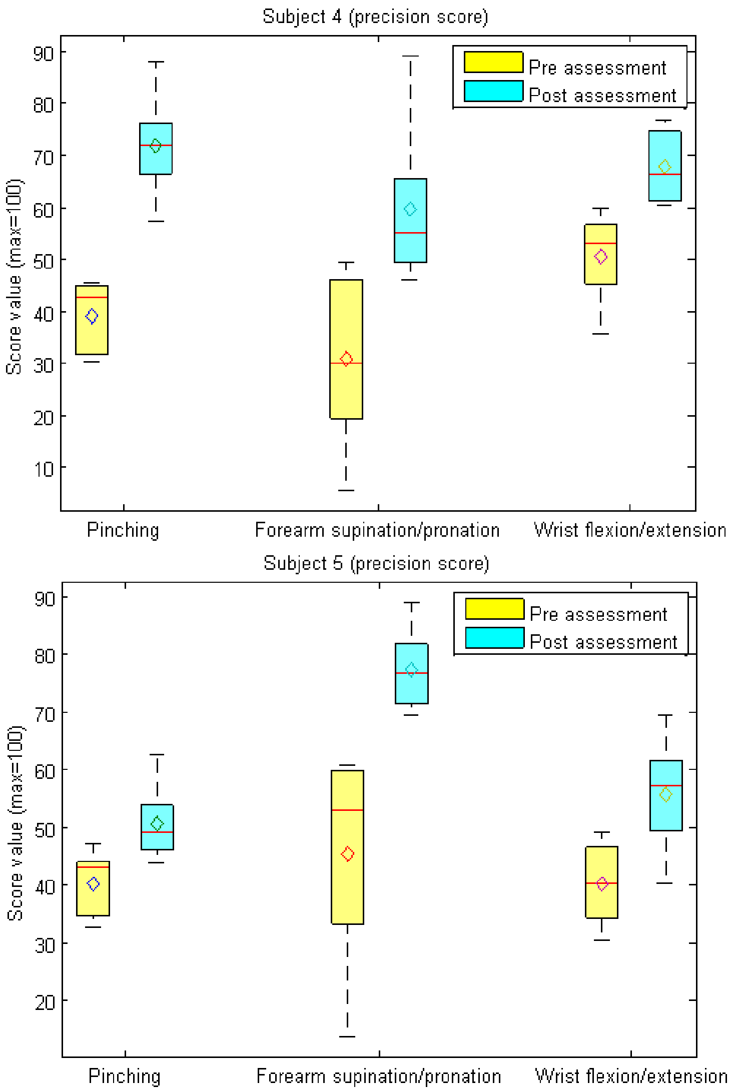


Figure 6.24: *Precision scores* of the subjects 4 and 5 before (pre) and after (post) the robotic therapy on the 3 exercises.

pinching exercise, 23% ($p = 0.007$) from $28.6°/s$ to $35.2°/s$ for forearm supination/pronation and 32% ($p = 0.047$) from $32.3°/s$ to $42.7°/s$ for wrist flexion/extension exercise. Subject 2 increased the *mean speed* by 61% ($p = 0.037$) from $21.6°/s$ to $34.9°/s$ for pinching exercise and 83% ($p = 0.02$) from $10.9°/s$ to $19.9°/s$ for forearm supination/pronation exercise. However, the *mean speed* for wrist flexion/extension exercise remained roughly the same (from $41°/s$ to $40.9°/s$). Subject 3 significantly improved the *mean speed* by 72.5% (p=0.002) from $23.7°/s$ to $40.8°/s$ for the pinching exercise. Nevertheless, the *mean speed* in forearm supination/pronation exercise was only slightly improved by 4.3% ($p = 0.133$) from $24.3°/s$ to

$25.4°/s$. In addition, the *mean speed* in wrist flexion/exntesion exercise decreased by 14% from $46.6°/s$ to $40.2°/s$. Subject 4 improved the *mean speed* by 13.5% (p=0.026) from $25.5°/s$ to $29°/s$ for pinching exercise, 18% ($p = 0.014$) from $28.5°/s$ to $33.7°/s$ for forearm supination/pronation and 14% ($p = 0.013$) from $28°/s$ to $32°/s$ for wrist flexion/extension exercise. Similarly, subject 5 improved the *mean speed* by 17.8% (p=0.176) from $25.2°/s$ to $29.6°/s$ for pinching exercise and 29% ($p = 0.002$) from $18.4°/s$ to $23.7°/s$ for forearm supination/pronation. However, no improvement was found in the *mean speed* of wrist flexion/extension exercise after the robotic therapy.

For the five subjects, all of them performed better in terms of *mean speed* for the pinch and forearm rotation exercises. However, no improvements were found in wrist flexion/extension exercise for subject 2, 3 and 5. The reason probably is the subjects were very good at wrist flexion/extension exercise before the robotic therapy. This could be seen from their high *success scores* and *precision scores*, as well as the high difficulty level (all level 6) used in the assessments. They could probably concentrate more on improving their *success scores* and *precision scores* since the two were the scores presented to them immediately after the trials. Another possible reason is the wrist extension/flexion exercise was not challenging enough for them as they could come to level 6 after the first session of trials.

Fig. 6.27 and 6.28 show the number of *velocity peaks* for the five subjects before and after the robot-assisted therapy for the three exercises. Subject 1 decreased the number of *velocity peaks* by 13% ($p = 0.046$) from 44 to 38 for pinching exercise, 21% ($p = 0.018$) from 49 to 38 for forearm supination/pronation exercise and 11% ($p = 0.15$) from 44 to 39 for wrist flexion/extension exercise. Subject 2's movements were less smoother compared to subject 1 which could be seen from the number of *velocity peaks*. Subject 2 decreased the number of *velocity peaks* by 42% (p=0.001) from

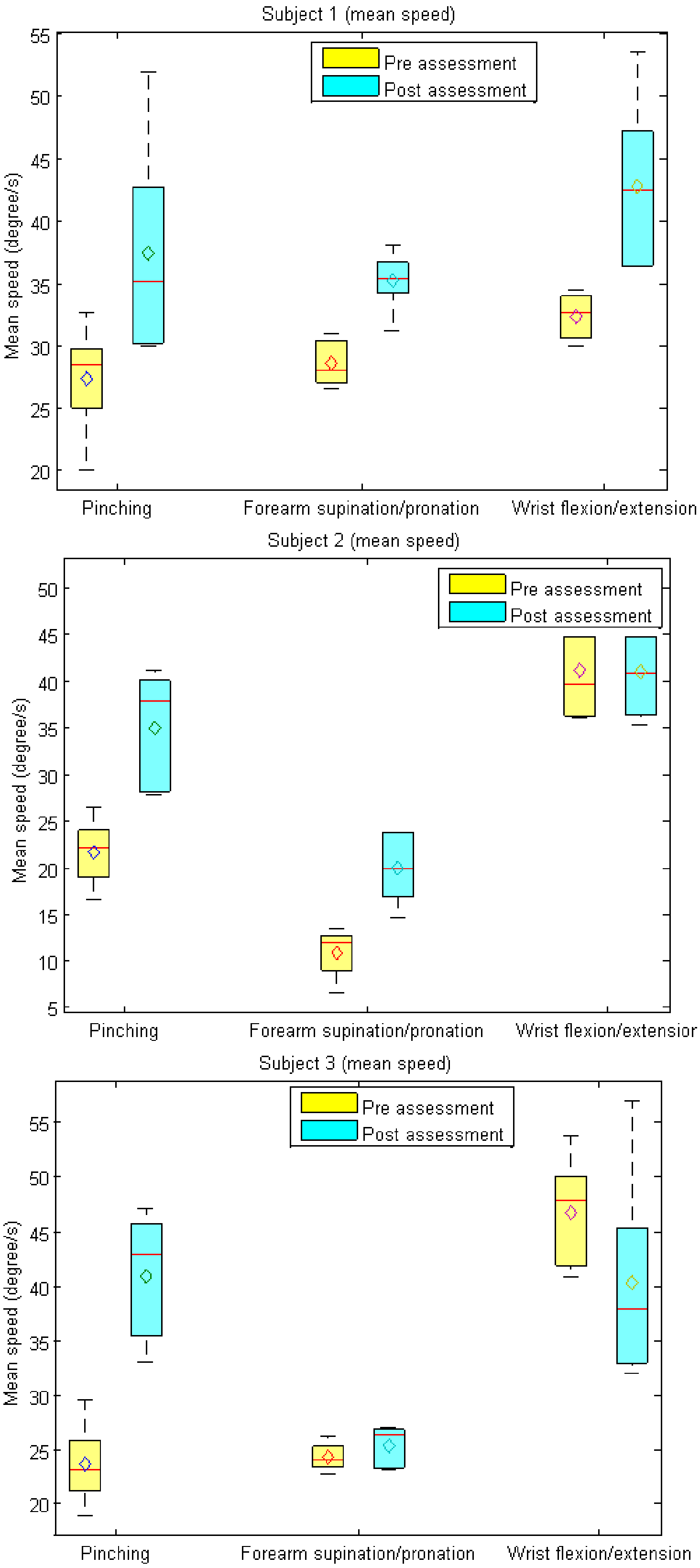


Figure 6.25: *Mean speed* of subjects 1, 2 and 3 before (pre) and after (post) the robotic therapy on the 3 exercises.

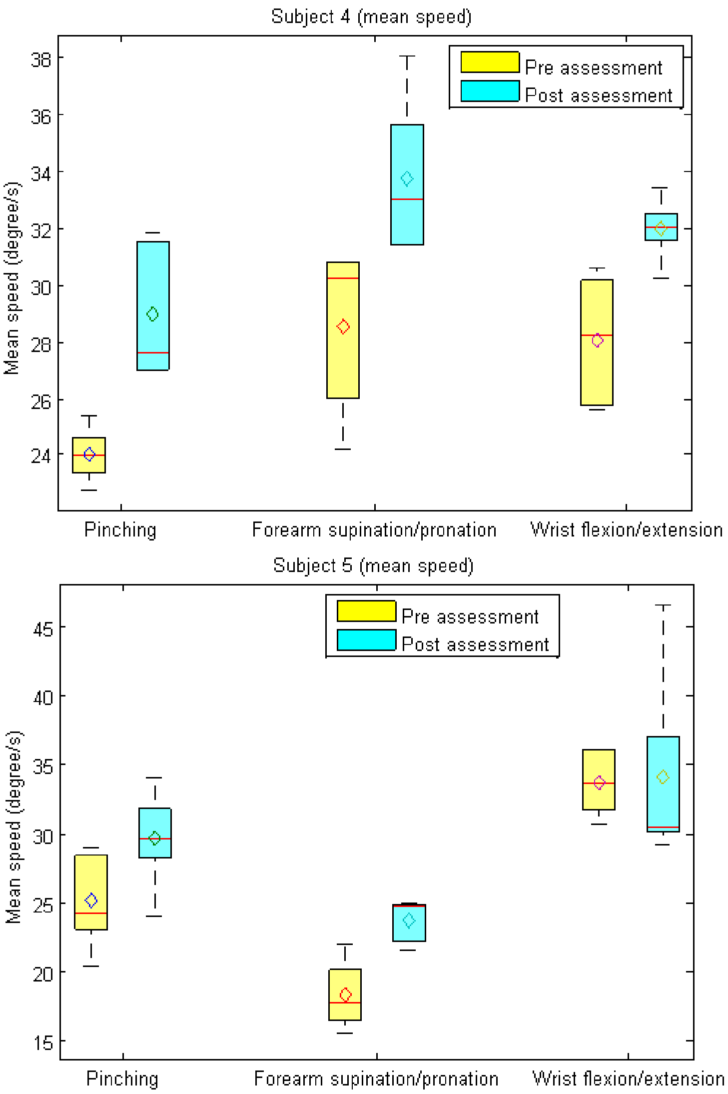


Figure 6.26: *Mean speed* of subjects 4 and 5 before (pre) and after (post) the robotic therapy on the 3 exercises.

94 to 55 for pinching exercise and 33% ($p = 0.033$) from 75 to 50 for forearm supination/pronation exercise. However, the number of *velocity peaks* in wrist flexion/extension exercise for subject 2 remained roughly the same (from 40 to 39). Subject 3 decreased the number of *velocity peaks* by 32.5% ($p = 0.002$) from 84 to 57 for pinching exercise and 15% ($p = 0.225$) from 51 to 44 for forearm supination/pronation exercise. However, the number of *velocity peaks* was slightly increased by 6.7% from 39 to 41 for wrist flexion/extension exercise. Subject 4 decreased the number of *velocity peaks* by 23% ($p = 0.024$) from 69 to 53 for pinching exercise, 27% ($p = 0.025$) from

56 to 35 for forearm supination/pronation exercise and 24% ($p = 0.014$) from 49 to 36 for wrist flexion/extension exercise. Nevertheless, for subject 5, the number of *velocity peaks* remained roughly the same for the wrist flexion/extension exercise and a 14% ($p = 0.067$) decrease, from 94 to 81, was observed for pinching exercise. A significant decrease (30% and $p = 0.002$), from 76 to 53, was observed for forearm supination/pronation exercise.

For the five subjects, they all had smoother movements for the pinching and forearm rotation exercises after the robotic therapy. However, small or no improvements were found for the wrist flexion/extension exercise, which is in line with the *mean speed* results and the reason could be the same.

6.3.2 Functional assessments

The functional assessments were conducted by occupational therapists involved in the project.

Table 6.4 displays the measurements of ROM of the five subjects before (pre-assessment) and after (post-assessment) the robotic therapy (the opening range of motion was measured by the robot). The 3 months post-assessment results of subject 1 2 and 3, who had completed it by the time of writing this thesis, were also presented. It can be seen from the table that subject 1 increased the forearm pronation range by 13.3% from 60° to 68°, forearm supination range by 8.6% from 70° to 76°, wrist flexion range by 6.7% from 60° to 64° but no improvement was found for the wrist extension range after the robotic therapy. The hand opening range of the subject was beyond the measurement limit of the device (90°). Subject 2 significantly increased the opening range by 133% from 30° to 70° and the supination range by 90% from 20° to 38°. However, the pronation range and flexion range remained the same. Furthermore, the flexion range decreased

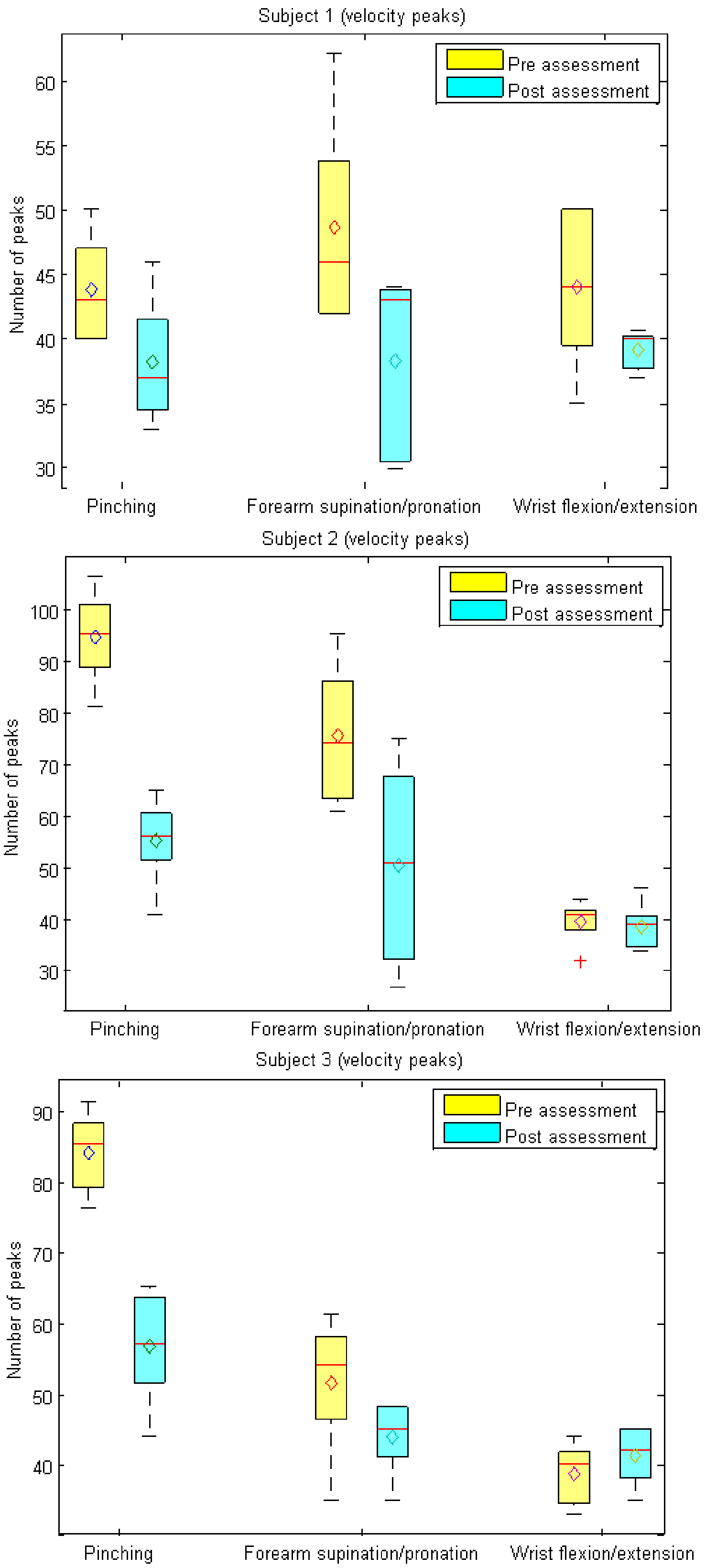


Figure 6.27: The number of *velocity peaks* in the speed profile for subjects 1, 2 and 3 before (pre) and after (post) the robotic therapy on the 3 exercises.

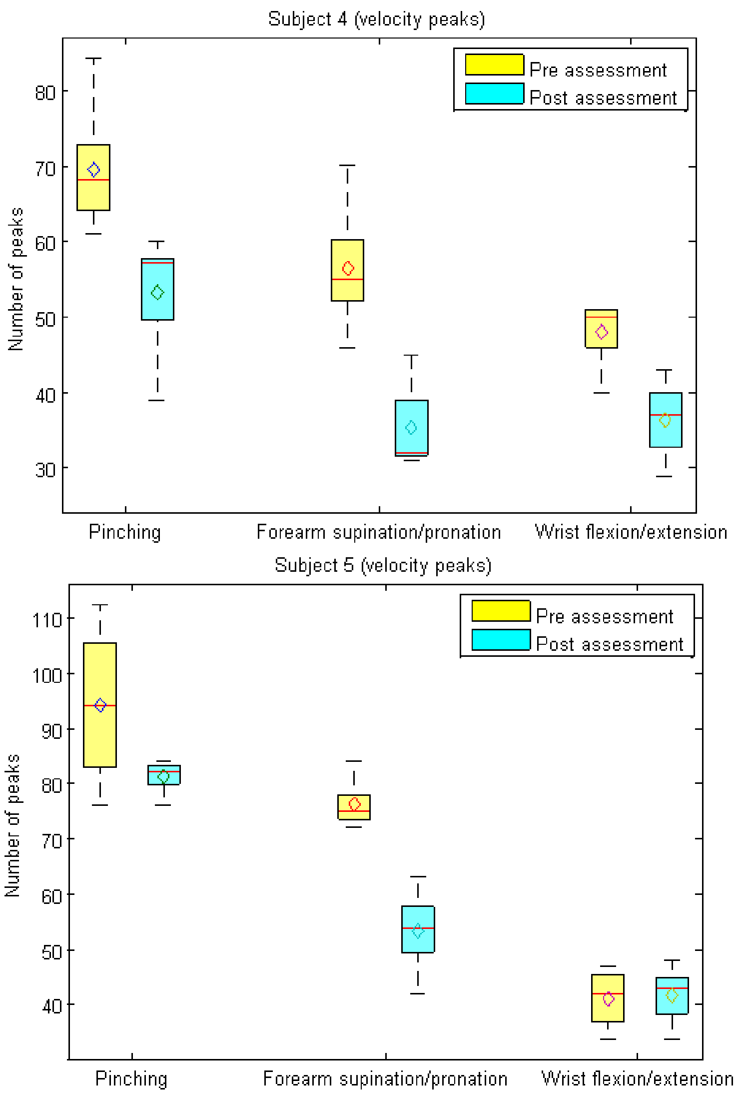


Figure 6.28: The number of *velocity peaks* in the speed profile for subjects 4 and 5 before (pre) and after (post) the robotic therapy on the 3 exercises.

by 9.3% from 75° to 68°. The reason could be the training range of wrist flexion/extension exercise is [-45 45]°, which is smaller than 75° the original flexion ROM of subject 2. Similarly, subject 3 significantly increased the opening range by 70% from 50° to 85°. Both the supination and pronation ranges remained the same (90°) before and after the robotic therapy. The flexion range increased by 7.7% from 78° to 84° and the extension range increased 2.9% from 70° to 72°. Subject 4 significantly increased the hand opening range by 20% from 75° to 90°, the forearm supination range by 13.8% from 58° to 66° and the wrist extension range by 5.3% from 57° to 60°. No improvements were found in the forearm pronation and wrist flexion ranges. Subject 5 significantly increased the hand opening range by 31.3% from 55° to 80°, the forearm supination range by 50% from 20° to 30° and the wrist extension range by 4% from 50° to 52°. No improvements were found in the forearm pronation and wrist flexion ranges.

In addition, most of the 3 months post-assessment results (9/12) improved, if they were compared to the pre-assessment results, suggesting that the beneficial effects sustained after the robotic therapy.

Table 6.5 shows the measurements of forces of the five subjects before and after the robotic therapy. Subject 1 increased his grip force by 29% from $2.3lb$ to $3lb$ and key pinch force by 7.1% from $3.5lb$ to $3.75lb$. Subject 2 increased his grip force by 8.7% from $2.3lb$ to $2.5lb$. His key pinch force was too small before and after the robotic therapy. For subject 3, the grip force remained the same ($1.5lb$). However, his key pinch force significantly increased by 16.7% from $1.5lb$ to $1.75lb$. Subject 4 slightly increased his key pinch force by 4.6% from $2.17lb$ to $2.27lb$ and significant improvement (49.3%) was found in the grip force. Subject 5 significantly increased his grip force by 28.2% from $1.17lb$ to $1.5lb$ and significant improvement (≥+100%) was found in the key pinch force.

In addition, most of the 3 months post-assessment results (4/6) increased, suggesting that the beneficial effects on forces were sustained after the robotic therapy.

Table 6.6 presents the measurements of motor skills (BOT-2) of the five subjects before and after the robotic therapy. The fine motor precision score of subject 1 didn't change, which is inconsistent with the result of robotic therapy and the 3 month post assessment result with an increase of 1 year. It is possible that the subject may require more time to integrate this motor ability into improvements in function. The fine motor integration increased by 6 months from 8 years 10 months to 9 years 4 months and significant improvement was found in the manual dexterity, which increased by 2 years 9 months from 7 years 10 months to 10 years 7 months. Subject 2's fine motor precision score increased by 1 year and 1 month from 5 years 0 month to 6 years 1 month, fine motor integration increased by 6 months from 7 years 4 months to 7 years 10 months and manual dexterity score increased by 4 months from 4 years 4 months to 4 years 8 months. Subject 3's fine motor precision score increased by 9 months from 6 years 4 months to 7 years 1 month. However, his fine motor integration score significantly decreased by 4 years from 10 years 10 months to 6 years 10 months. According to the therapist, the reason should be the subject was too tired while he was performing the test and the 3 months post result (13 years 2 months) also indicated that the measurement was not correct. The manual dexterity score of subject 3 decreased by 3 months from 6 years 7 months to 6 years 4 months and significant decrease was found in the 3 months post-assessment results. According to the therapist, the reason should be that the parent of the subject ended up scolding the subject during the assessment due to his non compliance. The fine motor precision score of subject 4 remained the same. Her fine motor integration score significantly increased by 5 years 11 months and some improvement (3 months) was found in her manual dexterity measurement. Subject 5 significantly increased his fine motor precision score by 2 years 2 months from 6 years 10 months to 9 years. However, his fine motor integration score significantly decreased by 4 years 2 months and his manual dexterity score decreased by 1 year. According to the therapist, the subject felt tired and was not very cooperative while conducting the two assessments.

In addition, most of the 3 months post-assessment results (7/9) improved, suggesting that the beneficial effects on forces were sustained after the robotic therapy.

Table 6.4: Range of motion measurements before (pre) and after (post) the robotic therapy.

Subject	Pre/post	*Opening*	*Pronation*	*Supination*	*Flexion*	*Extension*
S1	Pre	NA	60	70	60	54
	Post	NA	68	76	64	54
	Change	NA	+13.3%	+8.6%	+6.7%	0%
	3 months post	Nil	68 ✓	78 ✓	62 ✓	56 ✓
S2	Pre	30	80	20	75	8
	Post	70	80	38	68	8
	Change	+133%*	0%	+90%*	−9.3%	0%
	3 months post	Nil	80	44 ✓	70	10 ✓
S3	Pre	50	90	90	78	70
	Post	85	90	90	84	72
	Change	+70%*	0%	0%	+7.7%	+2.9%
	3 months post	Nil	90	95 ✓	95 ✓	76 ✓
S4	Pre	75	90	58	80	57
	Post	90	90	66	80	60
	Change	+20%*	0%	+13.8%	0%	+5.3%
S5	Pre	55	84	20	80	50
	Post	80	84	30	80	52
	Change	+31.3%*	0%	+50%*	0%	+4%

Opening range was measured by the reachMAN2.
NA means the subject's ROM is out of the measurement range of the reachMAN2.
Nil means the measurement was not performed.
* means significant improvement.
✓means the beneficial effects sustained after 3 months.

6.3.3 Discussion

The objective of the clinical study was to evaluate the effectiveness of the reachMAN2 as a rehabilitation tool. Five subjects had completed their 4-week robot-assisted rehabilitation therapies by the time of writing this thesis.

All subjects felt comfortable, reported no pain and enjoyed the interaction with the device during the robotic therapy. Their parents, who went through the process along with their children, felt the robotic device helped the recovery process of their children. In particular, mother of subject 2 wanted to continue the robotic therapy after her child finished the 4-week robotic therapy because of the significant improvements she observed

Table 6.5: Forces measurements before (pre) and after (post) the robotic therapy.

Subject	Pre/post	*Grip force (lb)*	*Key pinch force (lb)*
S1	Pre	2.3	3.5
	Post	3.0	3.75
	Change	+29.0%*	+7.1%
	3 months post	3.0 ✓	3.9 ✓
S2	Pre	2.3	<1
	Post	2.5	<1
	Change	+8.7%	NA
	3 months post	2.5 ✓	<1
S3	Pre	1.5	1.5
	Post	1.5	1.75
	Change	0%	+16.7%*
	3 months post	1.5	2 ✓
S4	Pre	0.67	2.17
	Post	1.16	2.27
	Change	+49.3%*	+4.6%
S5	Pre	1.17	<1
	Post	1.5	2
	Change	+28.2%*	≥+100%*

throughout the process. However, we couldn't approve that due to the protocol of the therapy. In addition, the parents believed that their children really enjoyed and actively participated in the process, which may be different from physiotherapy with therapists. In the conventional physiotherapy session, no computer games, which could provide the subject a sense of accomplishment and feedback to encourage them to continue, were used and the children may be passively involved in the process. Furthermore, the available 3 months post-assessment results of the subjects suggest that the beneficial effects of the robotic therapy were sustained even after the robotic therapy.

Synthesis of clinical results obtained from robot assessments

Table 6.7 shows the summary of the clinical study results from the robot assessments. From the table, we can see all the five subjects improved in most of the metrics (53/60), which were the *success score*, *precision score*,

Table 6.6: Motor skill measurements of BOT-2 before (pre) and after (post) the robotic therapy.

Subject	Pre/post	*Fine motor* precision (*year:month*)	*Fine motor* integration (*year:month*)	*Manual dexterity* (*year:month*)
S1	Pre	6:10	8:10	7:10
	Post	6:10	9:4	10:7
	Change	0	+0 : 6	+2 : 9
	3 months post	7:10 ✓	10:10 ✓	8:7 ✓
S2	Pre	5:0	7:4	4:4
	Post	6:1	7:10	4:8
	Change	+1 : 1	+0 : 6	+0 : 4
	3 months post	5:11 ✓	6:10	5:1 ✓
S3	Pre	6:4	10:10	6:7
	Post	7:1	6:10	6:4
	Change	+0 : 9	−4 : 0	−0 : 3
	3 months post	7:1 ✓	13:2 ✓	5:7
S4	Pre	8:7	13:1	5:8
	Post	8:7	19:0	6:1
	Change	0 : 0	+5 : 11	+0 : 3
S5	Pre	6:10	13:0	7:10
	Post	9:0	8:10	6:10
	Change	+2 : 2	−4 : 2	−1 : 0

✓means the beneficial effects sustained after 3 months.

mean speed and *movement smoothness*, suggesting improvements in hand, forearm and wrist functions. Improvements were also found in range of motion, muscle strength and BOT-2 test results. For the five subjects, smaller improvement was found in wrist flexion/extension (with 8/20 significant changes) compared to the other two functions (with 16/20 significant changes for pinching exercise, 18/20 significant changes for forearm supination/pronation exercise) in terms of all the metrics, especially the *mean speed* and *movement smoothness* metrics. The reason could be the wrist extension/flexion exercise provided by the robotic device was not challenging enough, which could be seen from the levels of exercises and score values used in the assessments. Interestingly, the ROM of subject 1 still increased even though it was bigger than the ROM used in the robotic therapy prior to the robotic therapy. For example, the supination ROM increased from 70° to 76°. However, the ROM used in forearm supination/pronation training was [-50 50]°, which is smaller than 70°.

Table 6.7: Summary of the clinical study results.

Subject	Exercise number	Success score	Precision score	Mean speed	Motion smoothness
S1	1	↑; N	↑; Y	↑; Y	↑; Y
	2	↑; Y	↑; Y	↑; Y	↑; Y
	3	↑; Y	↑; N	↑; Y	↑; N
S2	1	↑; Y	↑; Y	↑; Y	↑; Y
	2	↑; Y	↑; Y	↑; Y	↑; Y
	3	↑; N	↑; N	→; N	→; N
S3	1	↑; Y	↑; Y	↑; Y	↑; Y
	2	↑; Y	↑; Y	→; N	↑; N
	3	↑; N	↑; Y	↓; N	↓; N
S4	1	↑; Y	↑; Y	↑; Y	↑; Y
	2	↑; Y	↑; Y	↑; Y	↑; Y
	3	↑; Y	↑; Y	↑; Y	↑; Y
S5	1	↑; Y	↑; N	↑; N	↑; N
	2	↑; Y	↑; Y	↑; Y	↑; Y
	3	↑; Y	↑; N	→; N	→; N

Exercise number 1, 2, 3 denote pinching, forearm supination/pronation and wrist flexion/extension exercise respectively.
↑, ↓ and → denote there is improvement, decline and not much change (within 5%) in terms of the specific metric.
N means no significant improvement ($p \geq 0.05$) was found. Y means there is significant improvement ($p < 0.05$).

Clinical results comparison with other studies

Our reachMAN2 therapy results were compared with clinical results obtained from one conventional rehabilitation study (Wuang and Su [2009]) and one study with the robotic device, NJIT-RAVR (Fluet et al. [2010]). In the comparison (Table 6.8), the post-assessment results of the 5 subjects involved in our study (i.e. results measured immediately after the robotic therapy) were used. Three measurements (fine motor integration results of subjects 3 and 5 and manual dexterity results of subject 5) were excluded from the comparison as obvious non-compliances were observed during the assessments according to the therapist. The changes (P) in Table 6.8 were calculated through the following formula:

$$P = 100\% \times (M_{post} - M_{pre})/M_{pre} \tag{6.1}$$

where M_{pre} and M_{post} are the mean measurement results of all involved subjects before and after the robotic therapy, respectively.

In the study of Wuang and Su [2009], a hundred children (41 female, 4-10 years old) were involved in the study. All children went through a conventional pediatric rehabilitation program, at least 1 day a week, for 4 months (Wuang and Su [2009]). Two BOT-2 assessments were performed by a certified occupational therapist before and immediately after the therapy. The comparison results (Table 6.8) indicate the percentage changes of the fine motor precision and manual dexterity results in the conventional therapy are higher than the changes obtained from reachMAN2 therapy. However, the fine motor integration change in reachMAN2 therapy is higher than the change in the conventional therapy. Overall, no significant differences can be observed from the two sets of results. Nevertheless, the subjects involved in reachMAN2 therapy only went through 10 hours robotic therapy in a month, yet subjects in the conventional therapy received 12 days therapy in 4 months. The comparison indicates robot-assisted pediatric rehabilitation might be a promising approach to redefine current clinical strategies used in pediatric rehabilitation.

In the study of Fluet et al. [2010], three girls and one boy (aged 5, 6, 12 and 11, respectively) performed NJIT-RAVR training 60 minutes and 3 times a week for the duration of a 3-week camp as part of an intensive training program that also incorporated a total of 5 hours of intervention including CIMT and intensive bimanual therapeutic interventions. Table 6.8 shows the subjects in NJIT-RAVR therapy improved more compared to our reachMAN2 therapy in terms of grip force. However, the key pinch force result obtained from reachMAN2 therapy is far better than the result obtained from NJIT-RAVR therapy, which may due to the pinch training provided by reachMAN2. Moreover, the grip force and key pinch force results in reachMAN2 therapy are in consistent with each other (i.e. similar observed changes). These may demonstrate the effectiveness of the hand training, which is essential in performing ADL (Lambercy et al. [2007]), offered by reachMAN2. In addition, the supination improvement obtained from our reachMAN2 training is better than the improvement obtained from NJIT-RAVR therapy, which further demonstrates the effectiveness of our reachMAN2 therapy as both robotic therapies provided forearm rotation training.

The comparison shows promising effects were obtained from our reachMAN2 therapy, indicating the potential of reachMAN2 as a rehabilitation tool. However, the role of robots in rehabilitation is not to simply replace the therapist: rather robots will complement conventional therapies (Lambercy [2009]).

Table 6.8: Clinical results comparison with therapeutic therapy (Wuang and Su [2009]) and NJIT-RAVR (Fluet et al. [2010]).

	reachMAN2	*Therapeutic therapy*	*NJIT-RAVR*
Fine motor precision change	11.9%	17.4%	N.A.
Fine motor integration change	23.7%	12.2%	N.A.
Manual dexterity change	13.3%	21.3%	N.A.
Grip force change	21.7%	N.A.	27.5%
Key pinch force change	19.6%	N.A.	2.5%
Supination range change	16.3%	N.A.	12.8%

6.4 Summary

Robot-assisted rehabilitation, a promising approach to reshape conventional rehabilitation therapies for adults which was illustrated by many studies (Dovat et al. [2008]; Lambercy et al. [2007]; Yeong et al. [2009]), has also shown some or even more promise in pediatric rehabilitation since children are both familiar with and interested in the technology and interactive computer games, as illustrated in this work. However, it requires further analysis and studies to better serve the needs of children with physical disabilities.

With the objective of evaluating the effectiveness of the robotic device reachMAN2 as a rehabilitation tool, a clinical study has been conducted at NUH, Singapore. The clinical study described in this chapter is still ongoing with planned 20 CP children to investigate the feasibility of using the reachMAN2 as a rehabilitation tool, analyse the reactions of CP children after training with the robotic device, and quantify potential benefits of therapy with the reachMAN2.

The results obtained in the clinical study showed significant improvements in their performances with the robotic device as well as in functional assessments, suggesting improvement in hand, forearm and wrist functions. In addition to clinical assessments, participants reported they were using their affected hand more than previously. In particular, one of the subjects' parent asked for additional robotic sessions due to the significant improvement she observed during the robotic therapy. Furthermore, the available 3 months post-assessment results of the subjects suggest that the beneficial effects of the robotic therapy were sustained even after the robotic therapy.

The clinical study results prove the potential of robotic systems and of the reachMAN2 for CP children. Each subject who participated in the robot-assisted rehabilitation therapy showed improvement in their hand, forearm and wrist functions after the therapy with the reachMAN2, which indicates the flexibility of the exercise to adapt to subjects with various impairment levels.

Chapter 7

Conclusions and outlook

7.1 Contributions

This thesis investigated robot-assisted upper limb rehabilitation for CP children. Its main contributions include:

1. The design and construction of a compact robotic device, including the control system with friction and gravity compensation, to train upper limb functions which are essential in ADL, taking the biomechanical requirements of subjects into account.

2. The development of the design criteria for computer games dedicated to pediatric rehabilitation. Based on the criteria, we implemented 3 computer games for the reachMAN2 to increase subjects' participation and engagement while training and motivate them to train as much as possible.

3. A pilot study based on human-robot interaction was conducted to evaluate the possibility to use the reachMAN2 by CP children and whether the whole robot system, the hardware and interactive computer games, can engage the children throughout a 60-minute robotic test.

4. A clinical study was conducted at the NUH, Singapore to evaluate the effectiveness of the reachMAN2 as a rehabilitation tool.

7.1.1 Development of the reachMAN2

Studies of robotic therapy for adults with physical disabilities due to stroke have been an active field of research for the last two decades and the results suggest that stroke patients can benefit from this kind of therapy. However, in contrast to robot-assisted rehabilitation in adults, only a few studies on children with physical disabilities have been performed, which were observed from the review in chapter 2. Moreover, currently, the therapy received by the children with physical disabilities are not enough since rehabilitation sessions with the physiotherapist are time-intensive and restricted by limited availability of therapists. Therefore, to improve the effectiveness of therapy in pediatric rehabilitation and to get better understanding of the principles underlying motor recovery in children, we developed a compact robotic device, the reachMAN2, to train pinching, forearm supination/pronation and wrist flexion/extension exercises, which are essential in ADL according to the therapists and doctors at the NUH.

The design and implementation of reachMAN2 was presented in chapter 3. Main features of reachMAN2 are highlighted as follow:

- It is compact, safe, easy to use and offer the possibility to train fingers/hand, wrist and forearm, whose functions are essential in ADL.
- The design of the robotic device takes the biomechanical properties of human hand into consideration. Redundant safety measures were also implemented.
- The innovative design of the handle based on a dedicated cam mechanism improves its comfort and avoids back and forth movement of the arm while performing hand opening/closing functions (Tong et al. [2014]). Moreover, the cam mechanism allows patients to exercise in a functional hand position to ensure comfortable interaction with the

device.

- Different finger fixtures can be used to train various hand functions such as pinching with the thumb and index finger and grasping with thumb and the other four fingers.
- Only two motors were used and the device is capable of training three functions. The switch time between each type of training is very short (approximately 2 minutes).
- The height of the device can be adjusted easily to suit users with different height, standing, seating or even wheelchair-bound patients.
- The control algorithm implemented with the friction and gravity compensation enables fine motion control with the robotic device.

7.1.2 Implementation of the computer games

The second part of this thesis consists of the development of the design criteria for computer games dedicated to pediatric rehabilitation. Based on the developed criteria from rehabilitation and children entertainment aspects, we implemented 3 computer games for the robotic device, which was investigated in chapter 4.

Firstly, we reviewed some of the computer games or virtual reality interfaces used in the principal robotic devices. We found that these virtual reality games were mainly designed to test the functionality of the developed hardware. However, careful attention must be given while designing the computer games for pediatric rehabilitation system to incorporate motivation for active participation since children generally only focus on stuff they are interested in and may refuse to use the system if they feel bored. Reviewing existing virtual reality games and the online games dedicated to children, we developed the design criteria from rehabilitation and children entertainment aspects for games dedicated to pediatric rehabilitation.

Secondly, according to the developed design criteria, active exercises were first selected in designing the computer games since active exercises initiated and controlled by the subject can build muscle strength and improve muscle coordination, thus leading to correct patterns of muscle activation and coordination (Hogan et al. [2006]). Various feedback methods, audio, video, haptic and psychological feedback, which are commonly used in the virtual reality games dedicated to rehabilitation, were reviewed and selected in designing the computer games.

Finally, 3 computer games aimed to train different aspects of motion control for each exercise (pinching, forearm supination/pronation and wrist flexion/extension) were developed. Adaptable difficulty levels of the games make the robotic system capable of being used by patients with different impairment levels. Various feedback and reward methods were employed to interact with children while using the robotic system and interesting cartoon characters, fruits and animals, which are very popular among children, were used to increase their interest to the games.

7.1.3 Pilot study

A pilot study with seven CP children based on human-robot interaction was conducted to evaluate the possibility to use the reachMAN2 by children and whether the implemented computer games can keep engaging the children users throughout a 60-minute robotic test, which would be used in the clinical study.

Questionnaires focusing on children and parents' direct feelings for the robotic system were designed and used to obtain direct responses from them. In addition to using questionnaires, whose results are normally subjective, facial expressions, body gestures and verbal behaviors of the children during the 60-minute tests were analyzed to obtain some more objective and detailed information on the children's feelings to the robotic system.

The results from the questionnaires and behavior analysis indicate that the children can comfortably interact with the reachMAN2. The implemented computer games can engage the children throughout a 60-minute test. Interestingly, younger children seem to be more interested in the games compared to older ones and all of them enjoyed the interaction with the robotic system.

7.1.4 Clinical study

Following the positive results from the pilot study, a clinical study was conducted at the NUH to validate the effectiveness of the reachMAN2 as a rehabilitation tool. The clinical study aimed to recruit 20 CP children and 5 of them had completed their 4-week robotic assisted physical therapy by the time of writing this thesis.

Five cerebral palsy children (ages 5, 7, 8, 12, 7; 4 males and 1 female) participated in the clinical study for 10 sessions of robot-assisted therapy, with 2 or 3 sessions a week and 10 sessions in 4 weeks. Each session lasted around one hour, during which the subjects trained pinching with the index finger and thumb, followed by forearm supination/pronation, then by wrist flexion/extension exercise for 15 minutes respectively. A two-minute break to rest was given while switching from one type of training to another. Robotic and functional assessments were performed before and after the robot-assisted therapy

The results obtained in the clinical study showed significant improvements in their performances, such as increases in movement precision and smoothness as well as movement mean speed, with the robotic device as well as functional assessments results such as increases in range of motion, muscle strength and the scores obtained in the subtests of fine motor precision, fine motor integration and manual dexterity of BOT-2 (Deitz et al. [2007]), suggesting improvements in hand, forearm and wrist functions after training with reachMAN2. Furthermore, the available 3 months post-assessment results of the subjects suggest that the beneficial effects of the robotic therapy were sustained even after the robotic therapy.

7.2 Publications

Patent Applications:

Chee Leong Teo, **Liu Zhu Tong**, Julius Klein, and Etienne Burdet. "Therapy device for training fine motor skills." International patent, no. WO/2015/057162, 2015 (published).

Journal Papers:

Liu Zhu Tong, Che Fai Yeong, Chee Leong Teo, Hian Tat Ong, Alejandro Melendez-Calderon, Julius Klein, Roger Gassert and Etienne Burdet. "reachMAN: a simple modular rehabilitation robot to train reaching and manipulation." (submitting).

Conference papers:

Liu Zhu Tong, Julius Klein, Seraina Anne Dual, Chee Leong Teo, and Etienne Burdet. "reachMAN2: A compact rehabilitation robot to train reaching and manipulation." In Intelligent Robots and Systems (IROS 2014), 2014 IEEE/RSJ International Conference on, pp. 2107-2113. IEEE, 2014 (published).

Liu Zhu Tong, Hian Tat Ong, Jia Xuan Tan, Jeremy Lin, Etienne Burdet, S. S. Ge, and Chee Leong Teo. "Pediatric rehabilitation with the reachMAN's modular handle." In Engineering in Medicine and Biology Society (EMBC), 2015 37th Annual International Conference of the IEEE, pp. 3933-3936. IEEE, 2015 (published).

Hian Tat Ong, **Liu Zhu Tong**, Jia Xuan Tan, Jeremy Lin, Etienne Burdet, Chee Leong Teo and S. S. Ge. "Pediatric rehabilitation of upper limb function using novel robotic device reachMAN2." International Association of Science and Technology for Development (IASTED), 2015 (accepted).

7.3 Outlook

Robot-assisted rehabilitation, a promising approach to reshape conventional rehabilitation therapies for adults which was illustrated by many studies (Dovat et al. [2008]; Lambercy et al. [2007]; Yeong et al. [2009]), has also shown some or even more promise in pediatric rehabilitation since children are both familiar with and interested in the technology and interactive computer games, as illustrated in this work. However, it requires further analysis and studies to better serve the needs of children with physical disabilities. The possible future works with reachMAN2 and for robot-assisted pediatric rehabilitation are presented as follows.

7.3.1 Improvements on the reachMAN2

Several modifications can be made for the reachMAN2 to better serve children with physical disabilities. First of all, although the switch time between each type of therapy is short, it would be better to simplify the process, such as pressing a button or turning a knob, thus enabling any user without specified knowledge to operate. Secondly, the current real-time controller a desktop PC is relative bulky and replacing it with a smaller embedded system will significantly reduce the weight and size of the reachMAN2. Finally, the Host PC used to run and display the interactive computer games can be replaced with tablet PC and integrated with the robotic device, thus further reducing the size and weight of the whole system.

In both the conventional and robot-assisted rehabilitation methods, intensive movement repetitions involving the affected limb are required. Subjects may feel bored after several repetitions and then become less involved and concentrated, leading to undesirable effects. Therefore, more computer games can be developed to provide more options for the patients such that they are continually attracted for a much longer process of rehabilitation.

The clinical results show that smaller improvement was found in wrist flexion/extension compared to the other two functions, i.e., forearm supination/pronation and wrist flexion/extension functions. The reason could be the wrist extension/flexion exercise provided by the robotic device was not challenging enough. Therefore, in future, more challenging exercises should be implemented in the robotic system.

7.3.2 Possible future work on robot-assisted pediatric rehabilitation

Interactive games in pediatric rehabilitation

In developing robotic devices for rehabilitation, appealing computer games produce a significant increase in patients' motivation, thus promoting motor recovery (Flores et al. [2008]). Therefore, the combination of robot-assisted rehabilitation and appealing computer games to make full use of the robotic system is a real necessity for motor learning.

In addition, children are generally very keen to play computer games. It is reasonable to believe that appealing computer games may be more important and necessary compared to robot-assisted rehabilitation for adults.

However, according to my knowledge, few studies have been performed to investigate what kind of games are effective and what are the critical factors in designing appealing computer games for pediatric rehabilitation. A more comprehensive study is needed.

Whole task or several sub-tasks

It was observed that in healthy subjects, training several sub-tasks is a better way to learn complex task compared to learn the whole task directly (Frederiksen and White [1989]), which is generally used in robot-assisted rehabilitation. However, it would be interesting to investigate the difference between training only sub-tasks and a complete task in pediatric rehabilitation.

Robotic devices as assessment tools

In addition to provide therapy, robotic devices might be used as an assessment tool since the objective measurements of the robotic systems can be used to quantitatively evaluate progress made by subjects during the training. In particular, robotic devices are able to precisely measure parameters, such as position and force, and track the progress achieved by patients through the equipped sensors. Future robotic devices could potentially be used for standard clinical assessments to assess a patient's performances using measurements such as motion smoothness and precision, range of motion, stability and task duration.

Home rehabilitation

One of the main objectives of this work is to perform rehabilitation at home. Allowing patients to train at home without the costs of transportation and therapists may be a promising solution to increase the amount therapy with minimal cost. To achieve such goal, robotic devices should be safe, easy to use, able to adapt to various subjects and with reasonable cost.

Finally, robot-assisted pediatric rehabilitation is relatively new and only a few clinical studies have been conducted to evaluate the effectiveness and potential of robot-assisted rehabilitation. More clinical studies should be performed to collect more data to prove the effectiveness of robot-assisted in pediatric rehabilitation.

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